52-11-14438

TECH. NOTE
R.P.D.65

UNCLASSIFIED

TECH. NOTE
R.P.D.65

~~LIMITED DOCUMENT. NOT TO DISTRIBUTED FURTHER~~

~~SECRET~~

Royal Air

ROYAL AIRCRAFT ESTABLISHMENT

FARNBOROUGH, HANTS

TECHNICAL NOTE No: R.P.D.65

INV 90

EXCLUDED FROM AUTOMATIC REGRADING;
DOD DIR 5200.10 DOES NOT APPLY

NITRIC ACID - KEROSENE ROCKET MOTORS:

INITIAL DEVELOPMENT WORK WITH IMPINGING JET TYPE INJECTORS

by

R.P.HAGERTY, Ph.D., B.Sc., K. MEIER

and W.E.WHEELER, A.M.I.Mech.E.

with an Appendix by
J.H.FRAUENBERGER, Dipl.Ing.,
ROCKET PROPULSION DEPARTMENT,
WESTCOTT

MINISTRY OF SUPPLY

S 110,724 (1)

21065-57-001
~~664203863~~

~~SECRET~~ Best Available Copy

UNCLASSIFIED

Inv 82

52AA-8146

~~SECRET~~

~~LIMITED DOCUMENT. NOT TO BE DISTRIBUTED FURTHER~~

U.D.C. No. 621.455-41 LATI 160487
10a

Technical Note No. R.P.D.65
10

April, 1952
6

2 ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

4 Nitric Acid - Kerosene Rocket Motors

Initial Development Work with Impinging Jet Type Injectors

by

R. P. Hagerty, Ph.D., B.Sc.,
K. Meier, and
W. E. Wheeler, A.M.I.Mech.E.
5

with an Appendix by J. H. Frauenberger, Dipl.Ing.
Rocket Propulsion Department, Westcott

SUMMARY

A description is given of the investigation of the design and operating requirements of nitric acid rocket motors with burners incorporating the impinging jet type of injector up to the stage of successfully running a motor of 2500 lb thrust, with regenerative cooling by the oxidant. The most promising type of burner proved to be that incorporating injectors of the 2:1 impingement type, i.e. two jets of the acid impinge on each jet of kerosene. With the most efficient of these burners, a mean specific impulse of 197 seconds was recorded for a number of firings at a combustion pressure of 294 lb/sq in (absolute), representing 87% of the maximum theoretical specific impulse or about 94% combustion efficiency. Combustion chambers with mild steel inner shell, 0.10 inch thick, were run successfully with regenerative cooling by the acid, at combustion chamber pressures of 294 lb/sq in (absolute), with acid coolant velocities of 12 ft/sec at the cylindrical part of the chamber and 27 ft/sec at the throat. The heat transfer requirement, however, appeared to be less stringent than such calculations as were possible had indicated. Reliable and smooth ignition was obtained with a third fluid (W.A.F.1).

---

1. Nitric acid
2. Kerosene
3. Injectors

I Hagerty, R.P.

~~SECRET~~

LIST OF CONTENTS

LIST OF TABLES

APPENDIX

LIST OF ILLUSTRATIONS

1 Introduction

In view of the set-backs encountered in the investigation of pre-mixing injectors for nitric acid - kerosene rocket motors[1], it was decided that it would be more worthwhile, at that stage of knowledge of the general design requirements of motors employing this propellant combination, to concentrate the limited effort then available on a study of injectors of more conventional type. Injectors of the impinging jet type had been successfully employed in motors using nitric acids as oxidants with hypergols and non-hypergols as fuels, both in Germany and in the U.S.A. Attention was, therefore, focussed on burners incorporating this type of injector.

It was realized that a quantitative comparison of injector efficiencies was hardly possible unless complete motors capable of firings lasting at least 30 seconds were developed, since it is impracticable to obtain accurate performance figures from shorter firings. The initial work described here aimed, therefore, at obtaining sufficient knowledge of the design and operating requirements of motors with impinging jet type injectors to make possible the development of a combustion chamber - burner combination to operate regeneratively cooled at a thrust within the range 2000 to 3500 lb, corresponding to the thrust requirements of contemporary projects.

Owing to the long delay in the manufacture of the combustion chambers designed for regenerative cooling, a large part of the work was confined to ignition tests in so-called "mock" chambers and to short firings lasting about 10 seconds in rather crude water-cooled tubes fitted with solid nozzles of copper or steel. Throughout the work described ignition was obtained by using a third fluid which is self-igniting with nitric acid, and the conditions for reliable ignition and take-over to the main fuel were fully studied as well as the requirements for safe shut-down. This stage of the work culminated in a number of firings with chambers regeneratively cooled by the oxidant; the thrust level was 2500 lb, and the duration was of the order of 40 seconds which represented the maximum capacity of the propellant tanks fitted in the emplacement.

Now that the objects of the initial investigation have been achieved, work is being continued in order to obtain further elucidation of design problems and thus improve the efficiency and reliability. The thrust level is being raised to 3500 lb and ignition by pyrotechnic means is being studied.

2 Basis of choice of operating conditions and design parameters

A revised thermodynamic assessment[2] of the nitric acid - kerosene reaction indicated that, at a combustion pressure of the order of 300 lb/sq in (absolute), the maximum performance in terms of specific impulse should be obtained at a ratio of approximately 4.4 parts by weight of 98% white fuming nitric acid to 1 part of aviation turbine fuel (commercial quality). The optimum mixture ratio changes very slightly with combustion pressure, e.g. at about 500 lb/sq in (absolute) it is between 4.4 and 4.5 theoretically, and this has been verified experimentally[3]. The maximum combustion temperature at a pressure of 300 lb/sq in (absolute) is reached theoretically at a mixture ratio of 5. In the present work, the mixture ratio was nominally that giving maximum performance, but in practice it varied between about 4/1 and 5/1 in individual firings, for a variety of reasons.

Considerations of heat transfer and weight of propulsion system, primarily for a missile with pressure feed, led to the choice of design chamber pressures of the order of 260-320 lb/sq in (absolute). It was decided from general experience that the characteristic length of the chamber for this initial work should be between 60 and 75 inches. For ease of manufacture a cylindrical configuration was chosen for the chambers and an internal cylindrical diameter of 8 inches was selected for two reasons (1) over the range of thrusts considered, 2000 to 3500 lb, the calculated chamber gas velocities of roughly 200 to 350 ft/sec appeared reasonable in the light of published data; (2) with the above characteristic lengths, the length and diameter are almost equal i.e. the chamber is approximately spherical and hence the ratio of the surface area to be cooled to the chamber volume is a minimum.

The burners were designed to fit into the end of the chamber, and the diameter of the burner face was, therefore, 8 inches. The sizes of the injection orifices, were chosen on the assumption that atomization, mixing and distribution improve as the diameter of injection orifices decreases. The orifice sizes were, therefore, largely fixed by the decision to make the kerosene holes as small as practicable for drilling in stainless steel, although it was borne in mind that these holes had to be kept free from blockage without using filters in the pipe lines. The size of the kerosene hole was normally of the order of drill No. 55 (diameter 0.052 in). The injection pressures were in the range of 80 to 200 lb/sq in, which gives suitable injection velocities while they are not impracticable from the point of view of propellant expulsion in a missile. Since the discharge coefficients could be assumed to be about 0.7, the number of orifices of selected size required for a given throughput of kerosene at a given injection pressure could be calculated. The size of the nitric acid orifices could then be worked out, according to the relative numbers of acid and kerosene orifices in the particular design. The orifice sizes were selected so that with equal injection pressures for both propellants, the correct throughputs and mixture ratio were obtained within reasonable limits e.g. the calculated value was between 4.2/1 and 4.6/1.

3 Experimental equipment

3.1 Test stand layout

The layout of the test rig is shewn diagrammatically in Fig.1 and is more fully described elsewhere[5]. The nitric acid tanks, of which there were two connected in parallel, held a total utilizable quantity of nearly 500 lb of acid, and consisted of a mild steel outer tube with aluminium liner[6]. The kerosene tanks, of which there were also two with a combined capacity of 150 lb of kerosene, were fabricated from high pressure gas cylinders. The propellant tanks were pressurized by nitrogen for the expulsion of the propellants. The kerosene tanks were vented through the control panel and the acid tanks through a separate vent valve actuated automatically by pressure change in the nitrogen feed line, direct venting being prevented by a non-return valve. As a safety measure, a solenoid valve was fitted so that the above mentioned vent valve could not be closed, and hence the tanks could not be pressurized until the safety plug was inserted in the firing panel. The quantities of liquids in the tanks were measured from sight level tubes, one for the two acid tanks and one for the two kerosene tanks. A drop in height of 1 inch denoted that 8.17 lb of acid or 2.92 lb of kerosene had been consumed.

The entry of the propellants to the burner was controlled by propellant control valves positioned close behind the burner. A dump valve was provided in each propellant line between the main valve and burner; these dump valves were open when the main propellant valves were shut and they were shut automatically when nitrogen pressure was applied to open the main valves. The dump valves, therefore, performed two functions - firstly they prevented any liquid from seeping through the main valves when shut and trickling through into the burner; secondly, in firings of regeneratively cooled motors they relieved the pressure in the coolant jacket of the chamber instantaneously at shut-down. The main propellant control valves were mounted behind a blast plate on the standard parallelogram type of stand[5], the burner being attached at the front of the stand. All pipes etc. exposed to the acid were of 18/8 stainless steel or of aluminium.

3.2 Propellant control valves

During the first part of this work, the main propellant control valves were of the type shown in Fig.2 and described in reference 5. Both the acid and the kerosene valves were operated by water pressurized by nitrogen, the water being admitted to both from a common valve which was operated pneumatically from a solenoid valve controlled from the firing panel. The times of opening of each valve and the time sequence of the valves were adjusted by fitting chokes to the actuating cylinder of each valve in order to meter the water from the common source. When a third liquid was used for ignition it was found that the nitric acid should be given a slight advance on the fuel. This requirement could be satisfied quite reliably. The time required for these valves to open to full flow was of the order 0.03 second (Fig.3).

About half way through the work reported, the separate valves were replaced by a coupled valve (see Fig.4 and Ref.5). In this valve, the acid and kerosene pintles were operated from a common piston which was moved hydraulically as described above. In theory, by adjusting the tappets on the cross-arm a slight lead could be given to either the acid or the kerosene. In practice, this method of arranging the relative timing was not very satisfactory owing to jamming due to cross-cornering of the cross-arm. The relative timing was, therefore, obtained by contouring the pintles, which were also shaped so that the correct mixture ratio was maintained throughout the period of opening. This latter could be varied by metering the flow of water into the cylinder above the piston. During most of this work, the valve was adjusted to open fully in 0.5 to 1 second with very rapid build up to full flow. The valve was shut completely in about 0.2 second by dumping the water in the actuating cylinder. When a third fluid was used for ignition, it was found to be unnecessary to arrange critical matching during the period of pressure build-up; hence alterations in the pintle contours, which would otherwise have been required with every change of volume of the propellant pipe lines etc. downstream from the main control valve, were avoided; in fact very little time was spent in the adjustment of the pintle contours.

Typical records on the "Miller" recorder of the pressure build-up and shut-off for the two types of propellant control valves are reproduced in Fig.3.

3.3 Instrumentation

Thrusts were measured by means of a stainless steel bellows unit[5] connected to a Bourdon gauge, the whole being primed with kerosene. The unit was calibrated frequently against a master unit.

Propellant pressures in the pipes or burner passages were measured by the "Miller" recorder (made by William Miller Co., Pasadena, U.S.A.), and in the case of the kerosene by a Bourdon gauge and "Maihak" piston displacement type recorder in addition.

Combustion chamber pressures were measured principally by the "Miller" recorder, and on occasion additional measurements were made by Bourdon gauge and "Maihak" recorder. The "Miller" recorder is an electrical device, which produces on a strip of photographic paper a trace representing pressure together with a time base from a standard tuning fork. A carbon resistance or other type of electrical pressure pick-up is made one arm of a Wheatstone bridge; changes of pressure are converted to a bridge out of balance voltage which is amplified and applied to a mirror galvanometer, the deflection of which is recorded optically on photographic paper. The response can be made extremely rapid, the rapidity depending on the type of pick-up and galvanometer employed, and hence transients of high frequency can be recorded.

The complete priming with water or carbon tetrachloride of all pressure tapping lines was found to be essential to enable true records to be obtained, and was particularly important in the case of the combustion pressure tapping lines. If the latter were not primed fully, the small resultant flow of hot gas was sufficient to cause burning of the line at or near the entry from the chamber.

No instrument capable of measuring the temperature rise of the acid flowing through the chamber jacket was available during the course of this investigation and heat transfer figures were, therefore, obtained with water cooling. When the chamber was cooled with water, the two exits from the chamber jacket were choked, so that the pressure in the jacket was above chamber pressure. A flange type thermopile, (Fig.5), calibrated in conjunction with a suitable gauge, was located in each exit upstream from the choke, and the readings were checked against each other. The cold junctions were cooled by flow of mains water, the temperature of which was assumed to be the same as that of the water at the entry to the coolant jacket of the chamber. The coolant water was supplied from a tank pressurized by nitrogen, the tank being filled from the mains immediately before firing. The coolant flow rate was obtained from a calibration curve of the flow rate against the pressure difference between the tank and exit.

The gauge panel was photographed at 2-second intervals throughout firing. During most firings, the rocket motor itself and the flame were also photographed either by a cine-camera or by a repeating camera.

The duration of the firings was obtained from the time base on the "Miller" record and less accurately by means of an electric clock and stop watch.

4 Schedule of tests

4.1 Hydraulic testing of burner

The burner was first tested with water to check for leaks in the welds etc. and to check the impingement of the jet streams and the general spray pattern. The latter test was often made at mains water pressure. The burner was then flow tested with water on the test rig, (see Fig.6) and the following curves plotted:

(1) flow rate against burner injection pressure drop for the acid and kerosene orifices separately (from these the discharge coefficients were evaluated):

(2) combined flow rate against tank pressure for use during firings (see Fig.7). The flow rates with water were expressed in terms of the corresponding oxidant and fuel flow rates in the normal way, by applying the appropriate density corrections. During flow testing, the mixture ratio was adjusted, if necessary, by fitting a choke in the acid or kerosene line as required. If the injection pressures necessary to obtain the correct ratio had required some adjustment, this could have been made by redrilling some of the injection orifices (in fact this was never necessary). The valve timing was also adjusted in the course of these water flow tests.

4.2 Method of ignition

Ignition was obtained throughout the work described by means of a third fluid, W.A.F.1 which is a mixture of 70% furfuryl alcohol and 30% aniline by volume; W.A.F.1 ignites spontaneously with nitric acid with an ignition delay of about 10 milliseconds, at atmospheric temperature and pressure. The fuel line between the main kerosene valve and the burner was bent into the form of a U to accommodate up to one litre of W.A.F.1. When a firing was made, the W.A.F.1, therefore, entered the burner immediately ahead of the main fuel and the latter arrived about 0.2 to 0.4 second after the start, the precise time depending on the quantity of W.A.F.1 relative to the fuel flow rate, the valve timing and the volume of the burner passages. For the successful initiation of combustion by a third fluid, it is essential that ignition with the third fluid is smooth, and that the take-over to the main fuel is smooth and stable.

4.3 Initial firings

In the first of the series of burner tests, the burner was fired in the open (see Fig.8); observations and photographs were made of the behaviour and position of the flame at ignition, particularly at the take-over from W.A.F.1. to kerosene. With experience, it was possible by means of these tests to get a qualitative idea of the efficiency of the burner, and in fact a really poor burner could be virtually eliminated on the evidence of the open firing test alone. With a reasonably good burner, the flame with W.A.F.1 should be almost on the burner face and with kerosene it should not be more than a foot distant. During the change over period, the flame should not recede much past this distance. At all times, the flame should appear homogeneous, free from streaks and patches.

Summing up, a burner that appeared of poor efficiency in the open firing test was always bad when fired in a chamber, but a burner that was reasonable on this test was not necessarily satisfactory in a chamber. The open firing test is being retained for its usefulness in checking the timing of the propellant control valve and pressure build-up, and it is also useful in ensuring that water is swept out of the pipe-work and that the flow system is in order.

In the early work, the next stage consisted in firing with the burner fixed in an open ended tube of the same internal diameter and length as the intended chamber. The position of the flame zone in the tube could be estimated from the temper colour of the steel on the outside of the tube after firing.

The succeeding stage in the early work was to carry out firings with restricting chokes in the end of the tube, the size of the hole in the restrictor plate being gradually decreased and the combustion pressure thus raised successively from firing to firing. The purpose of this arrangement was to minimize damage to the rig and burner should explosions occur.

It soon became apparent that firing under these conditions actually encouraged mishaps. It appeared that combustion instability was almost certain to be present at the low combustion pressures and low characteristic lengths used for these firings; the inference drawn was that there was a minimum pressure and characteristic length required to avoid unstable burning. It was, therefore, decided to discontinue open tube firings and other firings at low pressures in the tube.

4.4 "Mock" chamber firings

The "Mock" chamber was originated in view of the crippling scarcity of complete chambers. The need was for a simple, readily fabricated chamber in which the first chamber firings of any new design of burner could be carried out, thus obviating the necessity of risking a complete chamber before the ignition and burning qualities of the burner were known to be satisfactory. The requirement was that the chamber should last intact long enough to cover at least ignition and take-over to the main fuel (i.e. say 3 seconds), and that it should be easily repaired or replaced with local facilities and, if destroyed, should cause a minimum of damage to other equipment. The original "mock" chambers consisted merely of a cylindrical portion fabricated from $\frac{1}{8}$ inch thick mild steel sheet, welded at one end to a flange for housing the burner and supporting the whole assembly on the test rig; the mock chamber was closed at the other end by a convergent portion fabricated similarly from sheet, with the orifice of the throat reinforced by a steel ring. The more sophisticated type developed later incorporated a machined burner flange with coolant annulus for water round the burner position in order to protect the burner; the chamber is completed by welding the sheet steel cylinder and nozzle on to the burner flange. Both types of "mock" chamber normally lasted for firings of from 5 to 10 seconds duration, depending on the combustion pressure. Usually, the steel ring parted from the conical portion more or less completely, and could later be rewelded quite simply to recondition the chamber. The throat (orifice) diameter, cylindrical diameter and characteristic length were usually the same as those of the intended complete chamber.

The "mock" chamber has proved so useful for the preliminary investigation of burner characteristics that its use now forms a standard stage in work on burners. The quality of the burner at this stage is largely judged from a study of the "Miller" firing records.

A few cylindrical jacketed tubes which could be fitted with solid copper or stainless steel nozzles were available. No great success was achieved with these, principally because the unsuitable material (which was the only one available at that time) and defective fabrication gave these tubes a short and unreliable life.

4.5 Firings in complete combustion chambers

A total of six chambers, designed for regenerative cooling by the oxidant, finally became available. Three of these (NA106) were designed for a thrust of 3500 lb and the remaining three (NA107) for a thrust of 2000 lb (see Appendix and Fig.9).

A number of firings were carried out with water cooling, in order to get some idea of the overall heat transfer rate, and these were followed by firings with cooling by the acid to obtain performance figures.

For firings with regeneratively cooled chambers the acid was fed from the propellant control valve to the nozzle end of the chamber jacket, then from the exit of the jacket through an external pipe back into the burner. The kerosene was fed from the propellant control valve, through the W.A.F.1 U-tube to an additional valve (see Fig.10). This valve was opened by an impulse from the acid line between the jacket exit and the burner entry. The function of this "delay" valve was thus to ensure that the fuel was delayed while the acid was filling the coolant jacket, so that the acid lead on entry to the burner, essential for smooth ignition with third fluid, was maintained. At shut-down, the propellants left in the acid pipes and passages downstream from the main propellant control valve were dumped through the automatically opened dump valves. This prevented the risk of explosion due to the dribbling of any of the residual propellants into the chamber; it also relieved the pressure in the coolant jacket of the chamber and removed the danger of the hot inner shell collapsing when it was no longer supported by the combustion pressure. The dump valve in the fuel pipe line was omitted in these tests, since the delay valve performed a similar function, at any rate in preventing the propellants from dribbling into the burner prior to firing.

The complete system was flow tested with water to check the flow characteristics and pressure losses before the first firing.

After every firing the burner was dismantled from the tube or chamber, then cleaned and examined, particularly for burning of the metal, "temper" colours and distortion, as well as "wash" and blockage of the injection orifices.

Similarly, the chambers were cleaned and checked for burning and distortion. After the regeneratively cooled chambers were fired, the jacket passages were flushed with water; the chambers were then dried inside and out by means of a hot air blower, and if they were not to be used again immediately, they were lightly oiled externally and internally including the coolant passages.

5 Summary of results and deductions

5.1 Burner designs with target plate

The first design of burner NA7 (shown in Fig.11) which was fitted in a water-cooled tube chamber, was inspired by the "Enzian" burner[7]. The injection orifices were arranged in three concentric circles, the centre one of which had a diameter of 6.4 inches and was, therefore, at a radial distance of about $\frac{3}{4}$ inch from the periphery of the burner plate. This circle of 30 orifices, drill No.55, (0.052 inch), was for the kerosene which was injected axially. The 30 orifices of the outermost and innermost circles, drill No.51 (0.067 inch), were for the acid, each pair of acid jets impinging radially on the corresponding kerosene jet at angles of 30°. The radial spacing between the circles of orifices was 0.35 inch, the distance of the circle of impingement from the burner face being $\frac{1}{2}$ inch, and the resultant direction of the spray being axial in the absence of the target plate. The peripheral target plate was inclined at an angle of 60° to the axis and was positioned so that the liquid streams hit it immediately after impinging mutually. The burner was constructed of stainless steel throughout and the target plate was of $\frac{1}{8}$ inch sheet and welded in place. The orifices gave a total throughput of 14.3 lb/sec at 140 lb/sq in injection pressure.

A series of twelve open firings, one without the target plate, were carried out to determine the best position of the target plate, which was as described above. Ignition, take-over and combustion with the main fuel were satisfactory, both with and without the target plate; in the latter case the flame was about 6 inches from the burner plate and in the former right on the burner. Fifteen firings were then carried out with the water-cooled tube chamber shown in Fig.11, at combustion pressures of 80 to 280 lb/sq in (absolute). The uncooled steel choke limited the duration of the firings to about 10 seconds. In the final test, a leak developed between the burner and the inner shell of the tube, resulting in the destruction of the latter.

The burner was then welded into a water cooled combustion chamber. After the first firing of 15 seconds duration, the target plate was found to be burnt in a castellated form and the chamber nozzle was also burnt in several places.

Attempts in two different ways, shown in Fig.12 to modify the chamber to provide cooling for the target plate proved unsatisfactory. These modifications, however, could hardly be said to have had a fair trial, as there were many mechanical difficulties and the chamber itself was not in any case suitable for use with nitric acid - kerosene. With the first design (see Fig.12(a)) the coolant velocity behind the target plate was insufficient to prevent the plate burning through after 4 seconds. In the second design, (see Fig.12(b)) the internal stresses were sufficient to cause the breakage of a welding seam.

It was, therefore, decided to determine whether it was practicable to dispense with the target plate. Further open firings seemed to show qualitatively little change in smoothness and stability of combustion. A series of firings of the "mock" chamber and the water cooled tube chamber were then carried out reasonably satisfactorily. The burner was finally destroyed by the burning out of the combustion chamber pressure tapping which passed through the burner.

The following deductions were made from these tests on burner NA7:

(a) Combustion with this burner was satisfactory without the target plate.

(b) A target plate of the area fitted could not be kept completely wetted, and, therefore, cool with the flow rate of propellants used.

(c) The difficulties of incorporating the target plate in the chamber wall made this solution impracticable and in view of the conclusion stated in (a) the extra complication did not appear to be justified.

(d) The flanging of the burner into the chamber must be completely gas-tight. This was achieved, on this and succeeding designs, by arranging the packing of the flange in such a way that it would be further compressed by the action of the chamber pressure on the burner.

(e) It was essential to prevent any appreciable gas flow into the combustion pressure tapping line, otherwise burnouts occurred at the entrance to this line. Elaborate precautions were, therefore, taken to prime this line completely with water and carbon tetrachloride.

(f) Slight burning of the burner face underlined the necessity for designing adequate cooling over the whole of the surfaces exposed to the combustion gases. In succeeding designs, both the acid and kerosene were used for cooling different sections of the burner face, the coolant velocities over the back of the burner face being kept up to at least 10 ft/sec.

(g) The burning of chamber surfaces also showed that it was essential that every square inch of chamber surface should be well cooled. In later designs, the burners were flanged so that they fitted far enough into the combustion chamber to overlap the coolant exit section where the coolant velocity in the chamber jacket would be less than elsewhere.

Burner NA12 (see Fig.13) for 3500 lb thrust, was of generally similar design to Burner NA7, except for the method of feeding the acid to the innermost circle of orifices. On water test, the spray pattern was seen to be poor, the jet streams from the inner row of (acid) orifices being fan-shaped instead of rod-like. Combustion in open firings and in "mock" chamber firings was rough, and no noticeable improvement was made by fitting a target plate. The cause of the poor spray characteristics, which produced poor combustion, was investigated and reported in a separate note[8].

It was concluded that if the impingement of the jet streams was definitely bad the fitting of a target plate led to only a slight, not a significant, improvement.

5.2 Burner designs without target plate

Two main types of impinging jet burners without target plate were investigated in the course of the work described. In all the designs, the circles of orifices were laid out so that the areas on the burner face inside and outside the circle of impingement were approximately equal. This arrangement was used because there had been indications with burner NA7 that the circle of impingement was too close to the burner periphery and chamber wall.

5.21 Burners with one to one impinging jets

For ease in manufacture, burner NA17 (see Fig.14) was designed in 99.8% aluminium. There was one circle of 30 acid orifices, drill No.42 (0.0935 inch), surrounding a circle with an equal number of kerosene orifices, drill No.55 (0.052 inch). The included angle between the jet streams was 90° radially, and the distance of the circle of impingement from the burner face was 0.4 inch, the resultant angle of spray being about 5° towards the axis.

Owing to the disparity in weight of the oxidant and fuel jet streams, the spray pattern on water test produced by this burner was not particularly promising in appearance, impingement not being complete and distribution somewhat uneven. Ignition, take-over and combustion, both in the open and in "mock" chambers, proved to be reasonably smooth and stable, however. In the first chamber firing, the edge of the burner was burnt slightly. The edge was, therefore, rounded off and no further trouble was encountered. This first burner was destroyed when the combustion chamber pressure tapping line broke, resulting in the complete burnout of the burner and chamber.

A second burner to the same design was made and some sixteen firings were carried out with fair success. Finally, the burner was made unserviceable when, owing to pickling of the welding, the back plate of the burner pulled out.

The work shewed that it was possible to cool an aluminium burner sufficiently to withstand exposure to the combustion gases of nitric acid and kerosene. The drawbacks of using aluminium for a test burner proved to be rapid wash-out of the injection orifices (particularly the acid), and poor mechanical strength in the welds after pickling in acid.

Burner NA18, which was similar to NA17, was made up in stainless steel. The only difference in the injection orifices was that they were brought closer together, the circle of impingement being only 0.2 inch from the burner face (see Fig.15). It was thought that better results would be obtained in this way; the only reason for not having the circle of impingement closer on the aluminium burner was that it was considered that the aluminium might have tended to burn if it had been so close to the flame.

Ignition, take-over and combustion proved satisfactory in "mock" chamber firings. A total of twelve firings were carried out in chamber NA106/1 with water cooling (see Table I). Pipe breakages, which were ascribed to combustion vibrations, occurred during four of the first five firings, though no damage was done to the equipment. The two-point suspension of the chamber on the test stand was, therefore, reinforced by the addition of two other suspension points, after which no further pipe trouble ascribable to combustion vibrations was encountered. Nine firings of up to 40 seconds duration were carried out with a coolant water flow rate of roughly 15 lb/sec and three with a flow rate of approximately 10 lb/sec. Measurements were taken of the coolant temperature rise on these firings and, in addition, reasonably consistent figures for specific impulse were obtained. The thrust ranged from 2250 to 2760 lb at a calculated combustion pressure in the region of 232 lb/sq in (absolute), specific impulse figures ranging from 151 to 189 seconds.

On the final firing, the combustion chamber burnt out round a section extending about 1 inch from the edge of the burner face. The face of the burner outside the circle of acid holes also burnt away. The failure of the chamber was ascribed to the thinning of the mild steel wall during previous firings (total duration 200 seconds).

With this burner, which used a one to one impingement system, combustion was reasonably smooth (see Fig.16) and efficiencies of 75% of the theoretical value were obtained during firings with water cooled chambers, the mean specific impulse being 166 seconds.

5.22 <u>Burners with two to one impinging jets</u>

In burner NA15, acid was injected through the outer and innermost circles of injection orifices (24 in each circle) and kerosene through the central circle (24 orifices); the acid - kerosene impingement angle was 45°, and the distance of the circle of impingement from the burner face was 0.2 inch (see Fig.9). The burner was made from stainless steel.

Ignition, take-over and combustion with this burner were notably smooth (see Fig.18). A firing was attempted with chamber NA106/2 regeneratively cooled by the acid, the propellant flow rates being 11.4 lb/sec for nitric acid and 3.1 lb/sec for kerosene. The firing was intermittent, owing, it was deduced, to the formation of gas in the coolant channels, and the inner shell of the chamber was distorted.

Seven firings at slightly lower propellant throughputs were carried out with chambers NA107/1 and NA107/2 at a thrust level of 2500 lb with a calculated chamber pressure of 294 lb/sq in (absolute), of firing duration 40 seconds and mean specific impulse 197 seconds. Of these firings, five were completely satisfactory (see Table II and Fig.17).

The success of the firings with regeneratively cooled chamber NA107 was very encouraging, since the chamber inner shell, of mild steel 0.10 inch thick, had been thought to be near the limit for cooling with coolant velocities as low as those employed (about 12 ft/sec on the cylinder and about 27 ft/sec at the throat). The efficiency obtained with this burner was also regarded as promising, the mean specific impulse of 197 seconds representing 87% of the theoretical specific impulse or about 94% combustion efficiency.

5.3 Heat transfer

In the firings made with combustion chamber NA106 and burner NA18, using water as coolant, the coolant temperature rise converted into rate of heat rejection to the coolant ranged from 0.41 to 1.99 C.H.U./sq in/sec, with a mean value of 0.93 (see Table I). The figures were obviously too divergent to be of much value, but a study of them would seem to suggest that the calculated rates of heat rejection (which were themselves likely to be wide of the mark) were possibly rather on the pessimistic side. Purely fortuitously, the overall mean figure for the practical measurements was quite close to the estimated heat rejection rate. If only those firings which were considered wholly satisfactory were taken into account, however, the mean heat rejection rate would be nearly halved, and about 0.5 C.H.U./sq in/sec.

No instrument for measuring nitric acid temperatures was available during the course of this investigation, so that no heat transfer figures could be obtained during the regeneratively cooled firings.

5.4 Ignition

With the burner designs described, reliable and smooth ignition under full flow starting conditions could be achieved with as little as 250 cc of W.A.F.1. It was found essential to ensure that the W.A.F.1 did not enter the injection orifices ahead of the nitric acid, otherwise pressure peaks were recorded in chamber firings. The allowable lead of acid was not determined, but did not seem to be critical, as reasonable ignition was noted on one occasion when, owing to valve leakage the chamber was full of acid up to the throat before fitting the dump valves. In order to get smooth ignition, the valves were set so that the acid pressure was built up in the burner passages about 0.1 second before the kerosene pressure.

5.5 Shut-down

No trouble was encountered at this stage, and no investigation was, therefore, carried out. There had been some evidence previously of minor explosions due to the slow closing of the main propellant control valves, or to the dribbling of propellant through these valves after shut-down, but such troubles were not met, possibly owing to the rapid closing of the valves used. In firings during which pipe breakages occurred, no explosion was remarked if the kerosene pipe broke but the firings usually ended with a bump if the nitric acid pipe broke.

6 Conclusions

(1) Ignition with a slug of 250 cc of W.A.F.1 in the fuel line

ahead of the main fuel proved 100% reliable up to a total combined throughput of propellants of 15 lb/sec, provided that arrangements were made for the acid to enter the injection passages of the burner before the W.A.F.1.

(2) No troubles were met when the propellant control valves were set to shut very rapidly (within 0.2 second) and when there was no dribbling of the propellants from the injection orifices.

(3) It was found that a peripheral target plate of stainless steel sheet was difficult to cool, and since it was doubtful whether, in fact, the presence of such a plate led to any significant improvement of efficiency, it was considered that the complication involved would not pay a worth while dividend.

The most promising two to one impinging jet type of burner without target plate had the following characteristics:-

Diameter of oxidant orifices	0.067 inch (drill No.51)
" " fuel orifices	0.052 inch (drill No.55)
Distance of circle of impingement from burner face	0.2 inch
Included angle of oxidant jets	90°
Resultant direction of spray	axial

Under the given firing conditions promising efficiencies (specific impulse 197 seconds i.e. 87% of the theoretical value) were obtained for a combustion chamber pressure of 294 lb/sq in (absolute), with regenerative cooling by the oxidant.

Direct comparison with the one to one impinging jet type of burner was not possible, since the latter burner was fired in a chamber with smaller characteristic length, (58 inches compared with 72 inches) at a lower combustion pressure (calculated value 232 lb/sq in (absolute)) and with water cooling instead of regenerative cooling. The combustion with the two to one design did appear from "Miller" pressure records to be more vibration free than with the one to one design. A comparison of the one to one designs, showed smoother combustion with the stainless steel burner than with the one of aluminium because the circle of impingement was closer to the burner face.

As regards burner materials, this work showed that stainless steel was most suitable for continuous use with nitric acid. With this material, the burner face (thickness 0.15 inch) was adequately cooled by utilizing either the acid or both propellants with a minimum velocity of 10 ft/sec behind the face. Aluminium could be used for burners for limited operation, since it was practicable to cool the burner face (thickness 0.32 inch) by using both propellants for different sections, the minimum velocities being as above. For repeated use, aluminium proved to have two main disadvantages - rapid erosion of the injection orifices and the liability to corrosion of the welding seams. There was no great saving in weight by using aluminium instead of steel, since the burner made from the former was necessarily of thicker construction than one made of the latter.

(4) The necessity for maintaining a reasonable velocity (>10 ft/sec) of coolant behind every square inch of surface exposed to the combustion gases was underlined during this work. That the cooling requirements of nitric acid - kerosene motors may be met using the acid as coolant was shown by the success of the firings with regeneratively cooled chamber NA107, which had a fairly thick inner shell and reasonably attainable coolant velocities.

In firings at a calculated combustion pressure of 232 lb/sq in (absolute) with a chamber characteristic length of 58 inches and a burner of the one to one impingement type, slight after-burning was observed. This was hardly evident in firings with the burner of two to one impinging type, at a pressure of 294 lb/sq in (absolute), in a chamber of characteristic length 72 inches.

7 Further work

Further developments are already well advanced. These include the investigation of the requirements for reliable ignition by means of pyrotechnic igniters, the direct comparison under identical conditions of the efficiencies of one to one and two to one impinging jet type burner designs, and the general study of the effect of burner parameters, on burner performance from the point of view of efficiency and stability of combustion.

As regards combustion chambers, designs are in hand embodying the lessons learnt during this work e.g. it is proposed, since from considerations of heat transfer this seems possible, to increase the inner shell thickness on the cylindrical part in order to withstand higher collapsing pressures. The new designs have characteristic lengths between 60 and 65 inches. A thorough investigation of the minimum characteristic lengths of chamber acceptable with the various types of impinging jet burner is proposed.

In addition, instruments for measuring nitric acid temperatures are now available, so that it should be possible to obtain accurate figures of the heat rejection rates with regenerative cooling.

Since the thrust requirements of contemporary projects now lie in the region of 3500 lb thrust, the developments will be carried out at this thrust level. The indications up to the present time are that scaling up even from 2500 lb to 3500 lb thrust level raises fresh problems.

REFERENCES

No.	Author	Title, etc.
1	J.H. Frauenberger, F.C. Jessen, K. Meier, W.E. Wheeler	Exploratory Work with Pre-mixing Injectors for Nitric Acid-Kerosene Rocket Motors RAE Tech Note No. RPD 62, March 1952
2	W.H. Williams	Thermodynamic Charts for the Combustion Products of Nitric Acid and Kerosene RAE Tech Note No. RPD 33, July, 1950

REFERENCES (Cont'd)

No.	Author	Title, etc.
3	P.D. Verschoyle, B.F. Warner, L.A. Wiseman	Performance of propellant systems based on white fuming nitric acid. Part I Report E.R.D.E. 29/R/49, August, 1949
4	A.D. Baxter, J.H. Frauenberger	Influence of operating pressure upon the weight of liquid propellant rocket motors RAE Report No. RPD 8, July, 1950
5	R.P. Hagerty, W.E. Wheeler	Test bed equipment for work on nitric acid - kerosene rocket motors RAE Tech Note No. RPD (In draft)
6	W.E. Wheeler	Aluminium lined high pressure vessels for use with rocket propellants RAE Tech Memo No. RPD 12, August, 1949
7	Major N.M. Harris, R.E.M.E.	The guided AA rocket "Enzian" RAE Report No. RPD 6, September, 1947
8	R.P. Hagerty, F.C. Jessen	Investigation of rough running of a rocket burner with observations on "Short Tube" injection orifices RAE Tech Note No. RPD 51, June, 1951

Attached:

Drg. Nos. R.P.800 to 820

Advance Distribution:

CS (A)	
CS (M)	
Chairman A.D.B.	
PDSR (A)	
PDSR (D)	
DGWRD	
DDGWRD	
GW3	6
DWRD	
D Eng RD	
Eng RD6	
DMXRD	
ERDE Waltham Abbey	6
Sec EDPC	
TPA3/TIB	180
DDRAE (W)	1
GW	3
Metall. Dept.	1
Chem. Dept.	1
Armament Dept.	1
Library	1
Structures Dept.	1
Mech Eng Dept.	1

APPENDIX I

The design of nitric acid - kerosene combustion chambers NA106 and NA107

by

J. H. Frauenberger, Dipl. Ing.

1 General

Combustion chambers NA106 and NA107 were constructed of identically the same materials and were generally similar in design. The outer shell and the cylindrical part of the inner shell of each chamber were machined from steel tube (G.C.Q. weldable). The nozzle portion of the inner shell was machined from steel billet and welded to the cylindrical portion. For spacing the inner and outer shells, when the chamber was being assembled and thus to provide the coolant passages, axial ribs were milled on the outside of the inner shell, fifty on the cylinder and smaller numbers on the straight lengths on the convergent and divergent parts of the nozzle. The height of the milled ribs was 1/16 inch which was the design width of the coolant gap throughout. The outer shell was not shaped, an aluminium filler being fitted round the nozzle portion of the inner shell to form the coolant passages. The coolant flow was axial from the exit end of the nozzle towards the burner end of the chamber. This design was selected on account of the low jacket pressure loss estimated. The nominal minimum thickness of the inner shell was 0.10 inch, and the thickness of the outer shell 0.15 inch.

In both chambers the differential expansion in an axial direction was taken up by allowing the outer shell to slide over the inner shell, the two shells being welded together only at the exit end of the nozzle.

Combustion chamber data

Combustion chamber	Cylinder diameter (in)	Throat diameter (in)	Exit diameter (in)	Length of cylinder from face of burner (in)	Combustion volume (cu in)	Characteristic length (in)	Weight complete with flanges (lb)
NA106	8.00	3.20	6.82	6.8	466	58	81
NA107	8.00	2.84	5.615	6.8	458	72	74

Combustion chamber NA106 was originally laid out for a thrust of 3500 lb, a specific impulse of 190 seconds and a combustion pressure of 370 lb/sq in (absolute) being assumed, chamber NA107 was laid out for a thrust of 2000 lb at a combustion pressure of 298 lb/sq in (absolute) for a specific impulse of 167 seconds. The assumed figures for the specific impulse were taken from German experience with mixed acid and petrol. The nozzle dimensions were obtained by using the charts in Ref.3. The nozzle angles selected were 90° and 30°.

Both these chambers were in fact fired at a thrust level of 2500 lb. Under these conditions the combustion pressures would be about 232 lb/sq in (absolute) for NA106 and 294 lb/sq in (absolute) for NA107, assuming a specific impulse of the order recorded; the nozzle of chamber NA106 would be over-expanding to some extent. In calculating the above pressures, the following expression was used:

$$F_a = S_F C_F P_c A_t$$

where

F_a is the actual thrust (2500 lb)

S_F " " nozzle thrust correction factor (assumed to be 0.95)

C_F " " " " coefficient (calculated value 1.415)

P_c " " combustion chamber pressure (lb/sq in (absolute))

A_t " " throat area (sq in)

2 Heat transfer and coolant velocities

Heat transfer estimations were made by the usual methods. In view of the uncertainties common to most such estimations for rocket motors, the heat rejection rate quoted below must be regarded as giving the order of magnitude rather than a definite figure. In chamber NA107 with regenerative cooling by the acid at 2500 lb thrust as fired, the maximum temperature of the gas side of the wall was estimated to be about 850°C. In chamber NA106 with water cooling during the firing, the wall temperature would be lower with a maximum temperature on the gas side of the wall at the throat as above of between 750° and 800°C.

The coolant velocities given below were calculated for the dimensions of the coolant passages as shewn on the drawings. During firing, owing to the expansion of the inner shell, the velocities, particularly on the cylindrical part, might be somewhat larger. The heat transfer rates and coolant velocities are given in the following table:-

/Table

Heat transfer and coolant velocities

	Combustion chamber NA106	Combustion chamber NA107
Coolant	Water	Nitric acid
Coolant flow rate (lb/sec)	15 (temperature assumed constant at 40°C for calculation of velocities)	10 (temperature assumed constant at 40°C for calculation of velocities)
Coolant velocity (ft/sec) divergent part of nozzle	46	25
at throat	51 (43 - 59)	27 (23 - 31)
convergent part of nozzle	41	20
on cylinder	26 (24 - 27)	12 (11.5-12.5)
max. possible velocity on cylinder	30	14
Overall heat rejection rate (C.H.U./sq in/sec)	measured 1.0 (approx.)	assumed 1.0
Area of cooled surface (sq in)	377	336
Rise in coolant temperature (°C)	measured 30 (approx.)	estimated ~ 80 (approx.)

Pressure loss in coolant jacket

This was evaluated by the use of standard formulae. In both chambers the losses due to changes of section and direction formed a large percentage of the total loss and amounted to over 50% in the case of NA107. The frictional losses were calculated using the Darcey-Weisbach formula, assuming for these calculations the friction factor to have a value of 0.025. (L.F. Moody. Trans. A.S.M.E., November, 1944).

The pressure drops were checked with water flow.

Pressure drop in combustion chambers NA106 and NA107

Combustion chamber	Flow rate (lb/sec)	Pressure drop (lb/sq in)	
		Calculated	Experimental
NA 106	15 (water)	64	
Chamber No. 1	15 (water)		85
" No. 2	15 (water)		71
NA 107	10.6 (nitric acid)	15	
Chamber No. 1	10 (water)		(19.5
	10.6 (nitric acid)		(14.5

TABLE I

FIRINGS WITH BURNER NA18 IN COMBUSTION CHAMBER NA106 - WATER COOLING

Characteristic length (as used) 58 in

Combustion pressure, at 2500 lb thrust, 232 lb/sq in (absolute) (calculated from $F_a = S_F C_F P_C A_t$)

Firing No.	Duration Sec	Propellant Feed Pressures psig: Oxidant (Miller)	Fuel: Gauge	Fuel: Miller	Fuel: Maihak	Combustion Pressure Miller lb/sq in Gauge	Propellant Through-put lb/sec	Propellant Mixture Ratio	Thrust lb	Specific Impulse sec	Coolant-Water: Flow Rate lb/sec	Coolant-Water: Temp. Rise °C	Heat Transfer Rate CHU/sq in/sec	Notes
2	13.8	320	300	285	302		15.2	4.1	2580	170	14.9	37	1.45	Fuel pipe connection came loose
3	7.4	280	300	295	296	-	15.9	4.1	2580	163	"	-	-	Fuel pipe connection broke
4	9.2	300	300	290	307	-	16.0	4.9	2500	156	"	34	1.33	Acid pipe connection broke
5	21.2	230	280	260	-	-	14.9	4.2	2250	151	"	11	0.43	Satisfactory firing
6	4.2	320	310	295	307	-	16.5	4.4	2550	154	"	15.5	0.61	Fuel pipe connection broke
7	17.9	320	-	295	307	-	14.9	4.9	2550	170	"	-	-	No gauge panel record - camera failure
8	16.4	295	-	280	296	-	15.2	4.6	2300	151	"	10.5	0.41	Acid pipe line found to be cracked
9	43.4	310	310	290	319	202	14.4	4.3	2500	174	14.5	16	0.61	Two thermopiles used in parallel and on succeeding firings
10	39.6	315	310	280	314	210	15.0	4.3	2405	161	"	16	0.61	Satisfactory firing
11	16.3	320	315	300	326	-	14.6	4.3	2750	189	10.3	73.5	1.99	Fuel pipe line dump valve opened
12	1.0	300	-	265	290	202	-	-	-	-	"	-	-	External fire at start
13	8.8	330	332	302	343	235	14.9	4.6	2760	185	"	-	-	Chamber burnt near burner

SUMMARY Mean Specific Impulse 166 sec (75% of the theoretical value with no allowance for nozzle losses etc.)
Mean Heat Transfer Rate 0.93 C.H.U./sq in/sec
or 1.67 B.T.U./sq in/sec

TABLE II

FIRINGS WITH BURNER NA15 IN COMBUSTION CHAMBER NA107 - REGENERATIVE ACID COOLING

Characteristic length (as used) 72 in

Combustion pressure, at 2500 lb thrust, 294 lb/sq in (absolute)(calculated from $F_a = S_F\ C_F\ P_C\ A_t$)

Firing No.	Duration sec	Propellant Feed Pressures psig				Propellant Throughput lb/sec	Propellant Mixture Ratio	Thrust lb	Specific Impulse sec	Chamber No.	Notes
		Oxidant (Miller)	Fuel								
			Gauge	Miller	Maihak						
5	36.3	407	362	400	355	12.4	4.9	2360	190	1	Satisfactory firing
6	39.2	380	-	330	-	12.3	6.9	-	-	"	Firing unsteady, due to ice in fuel pipe line
7	39.0	375	375	320	367	13.1	5.5	2495	190	"	Satisfactory firing. After firing, small hole on convergent portion of nozzle. Change in flame after 35 secs
14	40.4	330	382	400	384	11.45	4.2	2300	201	2	Pyrotechnic ignition. Satisfactory firing
15	40.6	400	380	325	384	11.9	4.3	2390	201	"	Pyrotechnic ignition. Satisfactory firing
16	41.0	325	380	402	372	11.55	4.1	2320	201	"	Pyrotechnic ignition. Satisfactory firing
17	12.2	380	-	385	384	17.45	6.3	2350	135*	"	Firing stopped itself. Inner shell of chamber found to have collapsed into ten corrugations

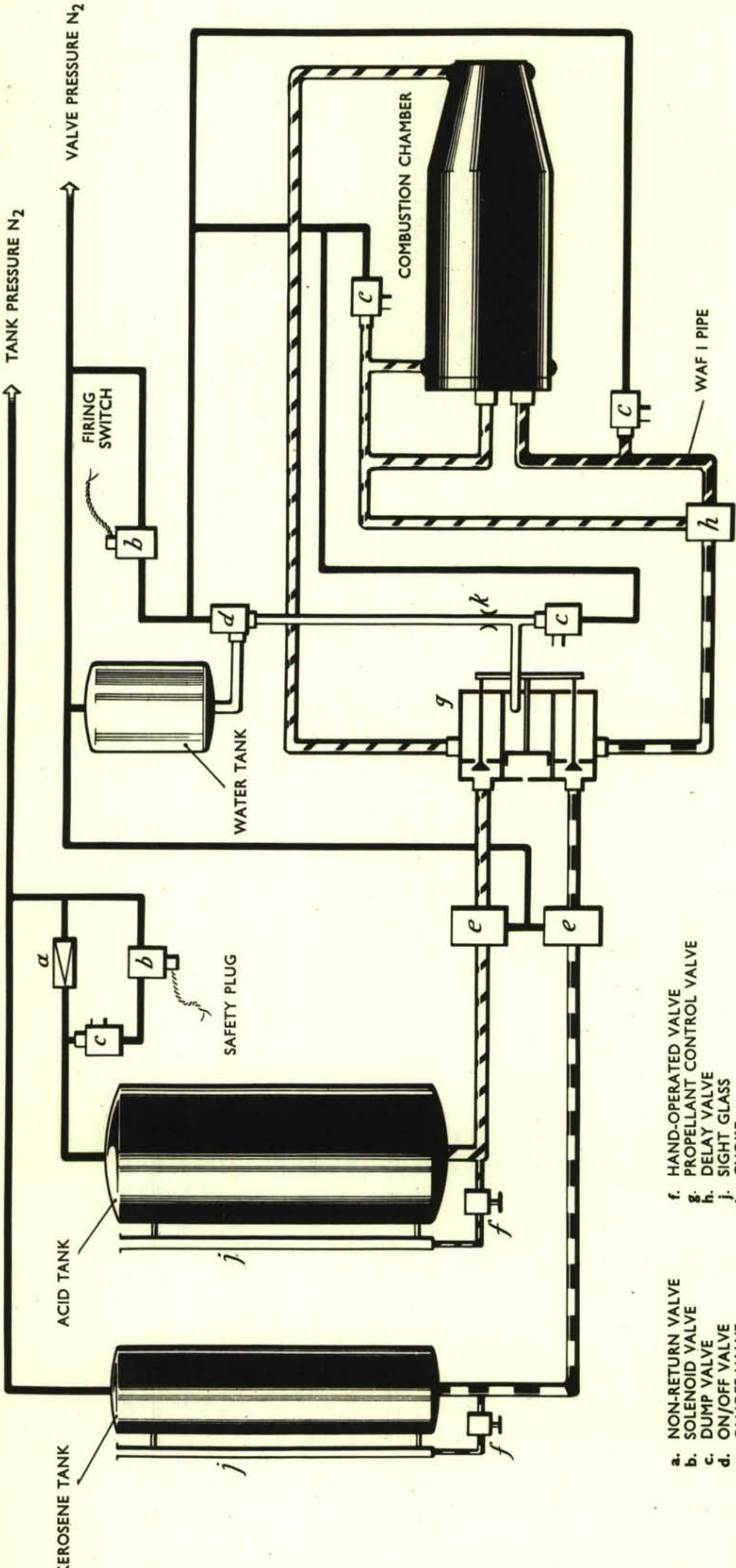
<u>SUMMARY</u> Mean Specific Impulse 197 sec (87% of the theoretical value with no allowance for nozzle losses etc.)
(neglecting firing No.17)

FIRINGS WITH BURNER NA15 IN COMBUSTION CHAMBER NA107 - WATER COOLING

Chamber No.1 was repaired, and firing No.12, at 2500 lb thrust, duration 40.2 sec, gave a heat transfer rate of 1.11 C.H.U./sq in/sec

During firing No.13, chamber No.1 was destroyed owing to failure of the coolant water supply

---



a. NON-RETURN VALVE
b. SOLENOID VALVE
c. DUMP VALVE
d. ON/OFF VALVE
e. ON/OFF VALVE
f. HAND-OPERATED VALVE
g. PROPELLANT CONTROL VALVE
h. DELAY VALVE
j. SIGHT GLASS
k. CHOKE

FIG. 1a. LAYOUT OF TEST-RIG
(COMBUSTION CHAMBER REGENERATIVELY COOLED)

FIG.1b

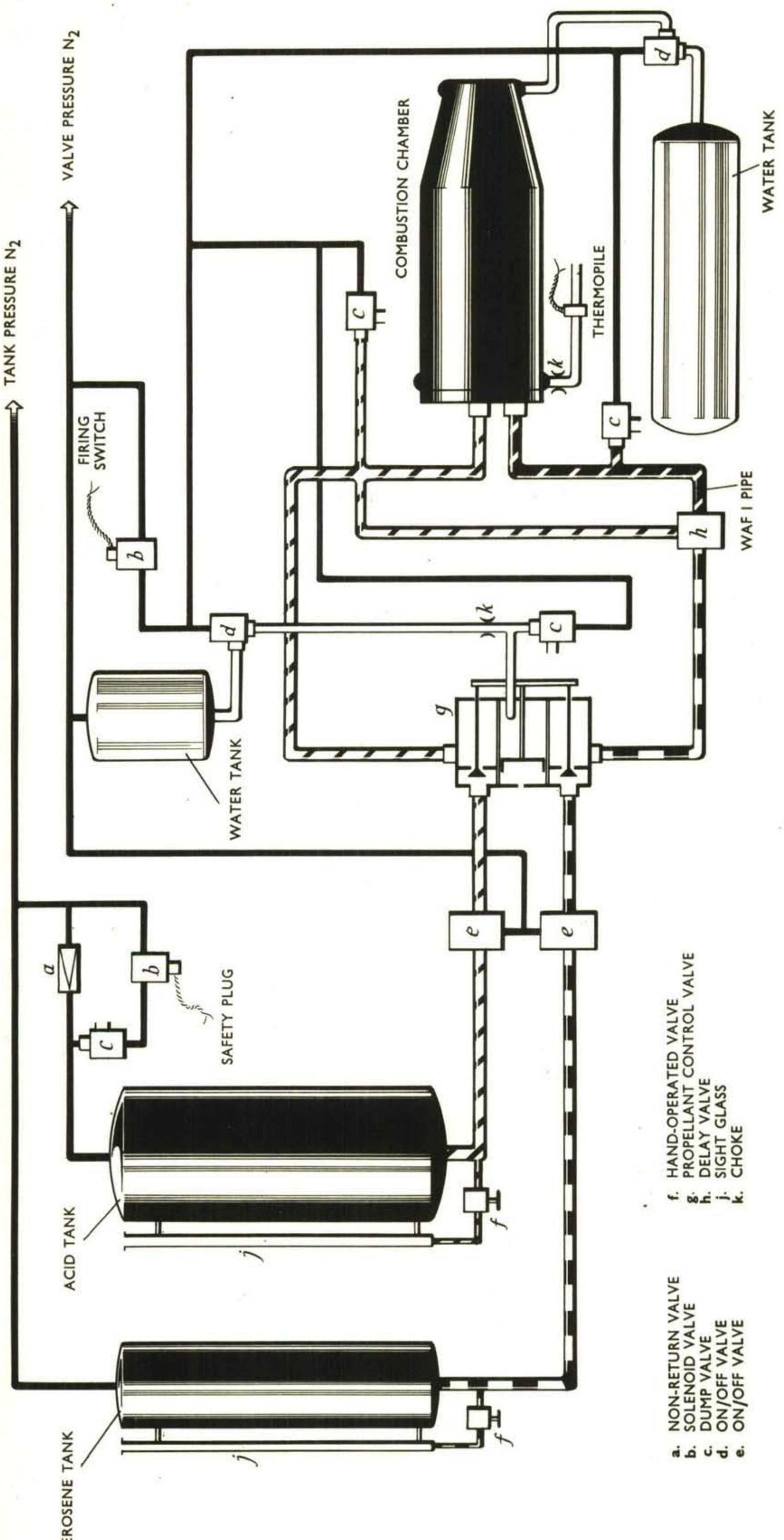
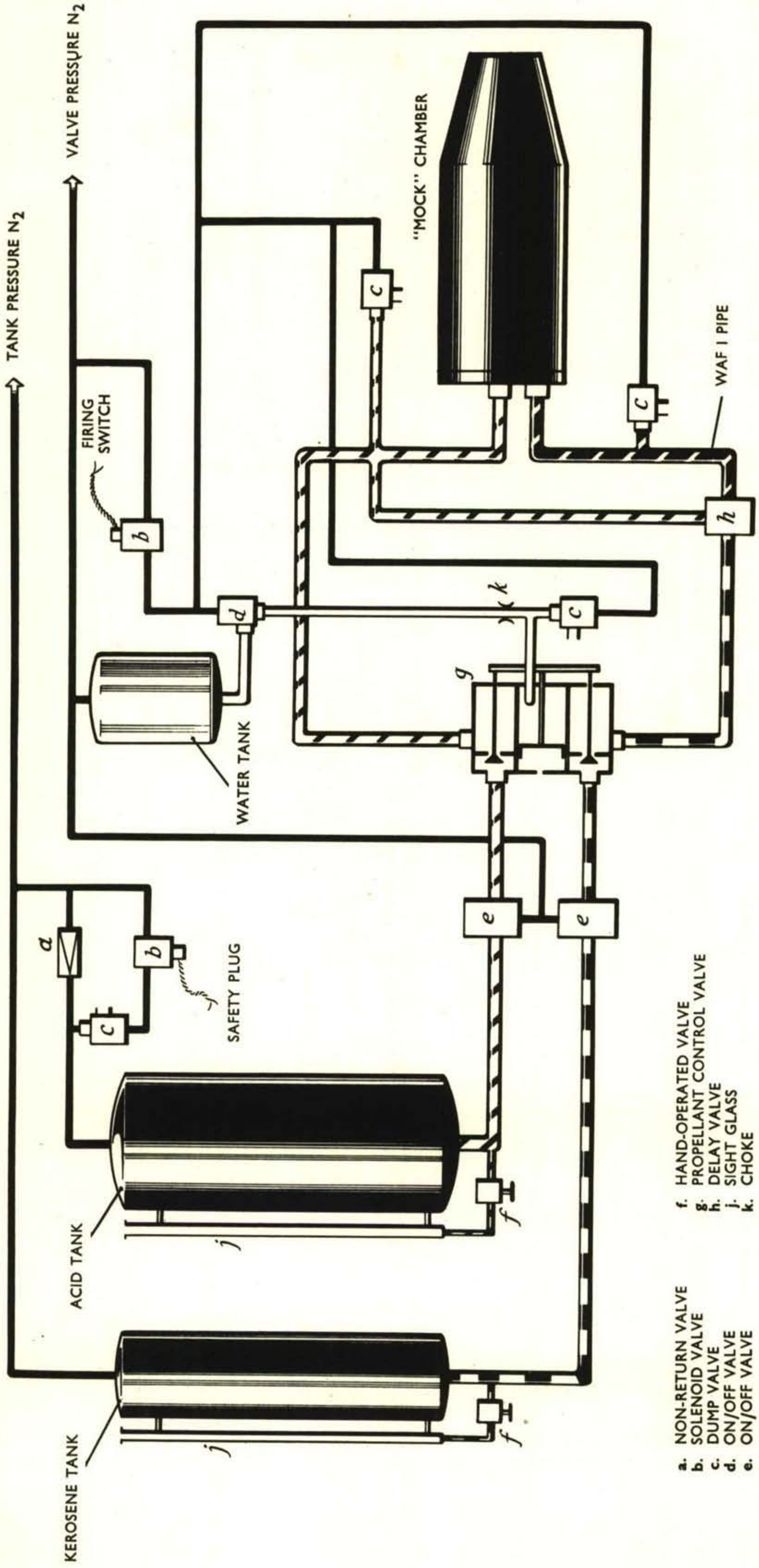


FIG.1b. LAYOUT OF TEST-RIG
(COMBUSTION CHAMBER WATER COOLED)

FIG. 1c



a. NON-RETURN VALVE
b. SOLENOID VALVE
c. DUMP VALVE
d. ON/OFF VALVE
e. ON/OFF VALVE

f. HAND-OPERATED VALVE
g. PROPELLANT CONTROL VALVE
h. DELAY VALVE
j. SIGHT GLASS
k. CHOKE

FIG. 1c. LAYOUT OF TEST-RIG (MOCK CHAMBER)

FIG.2

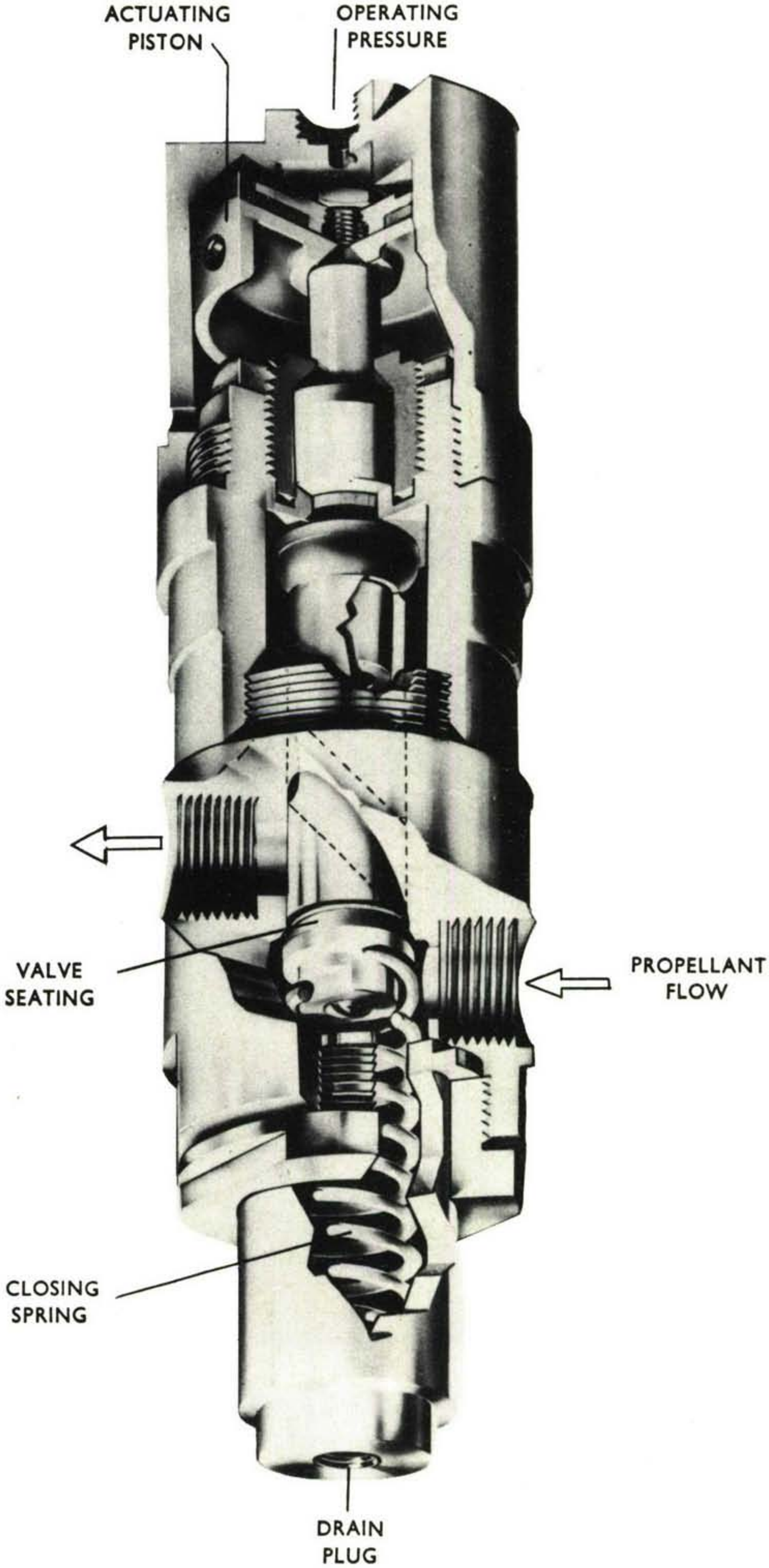


FIG.2. PROPELLANT CONTROL VALVE (FIRST TYPE)

FIG.3

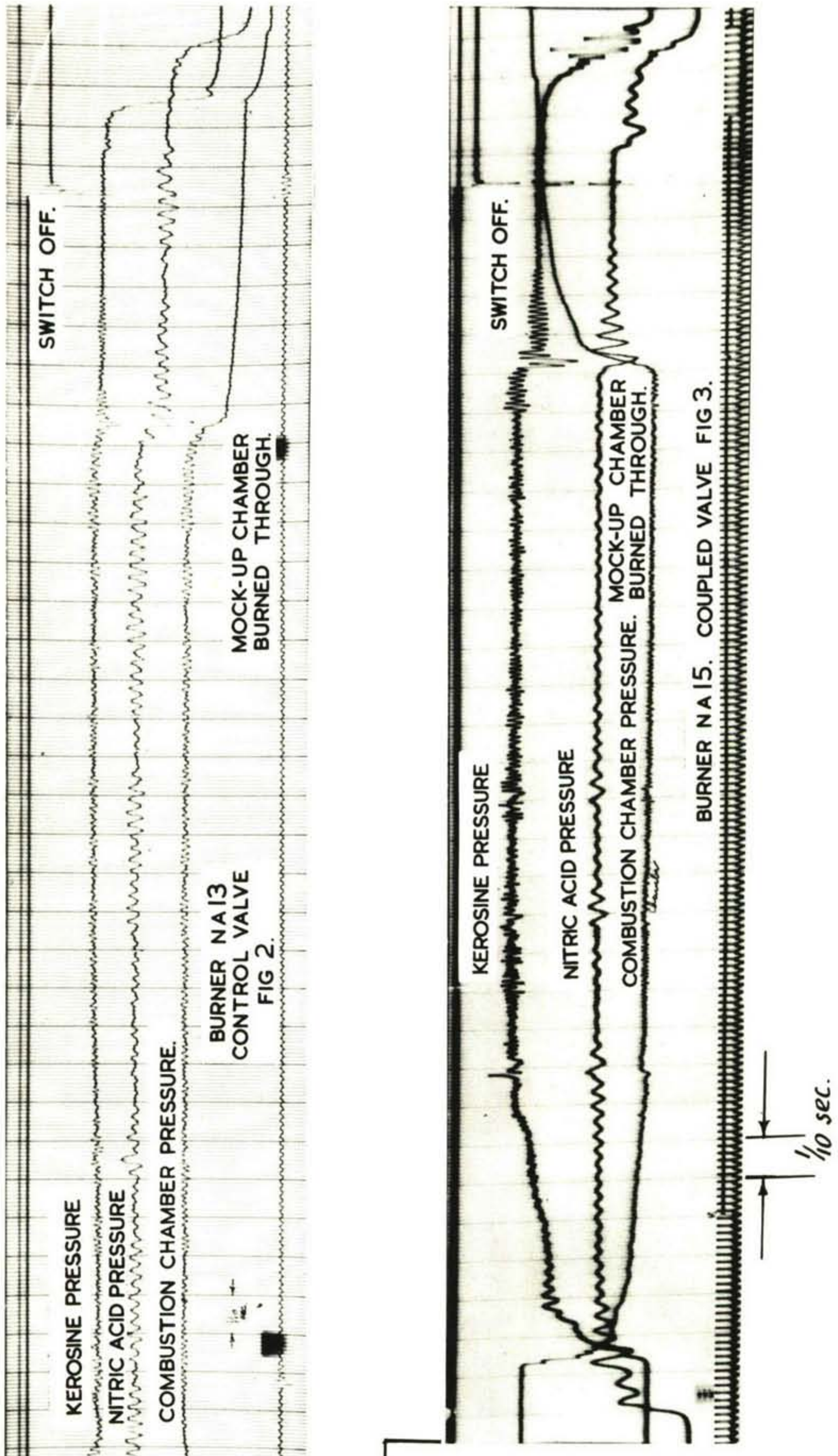


FIG.3. OPENING & CLOSING CHARACTERISTICS OF PROPELLANT CONTROL VALVES

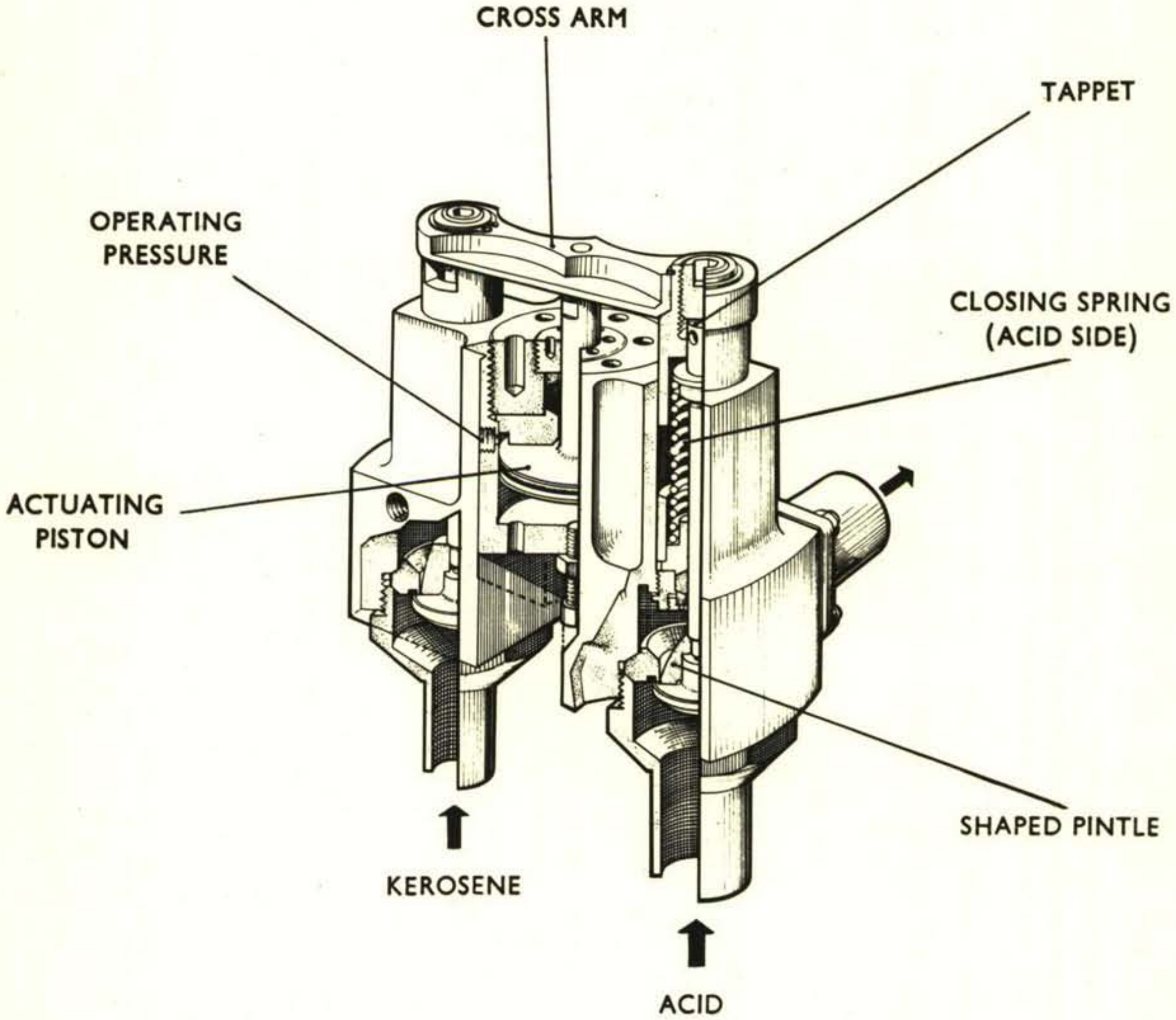


FIG.4. PROPELLANT CONTROL VALVE (COUPLED TYPE)

FIG.5

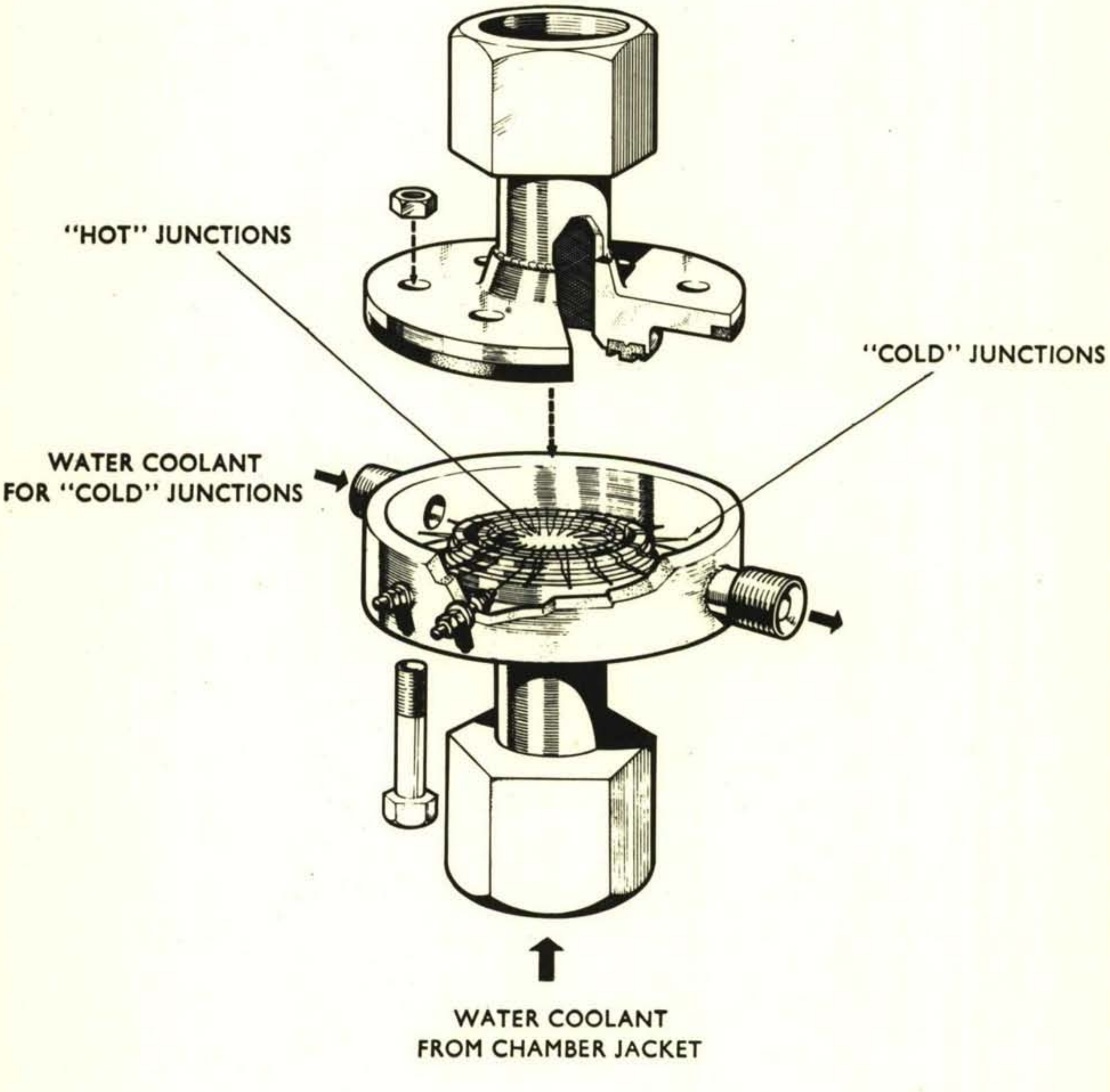
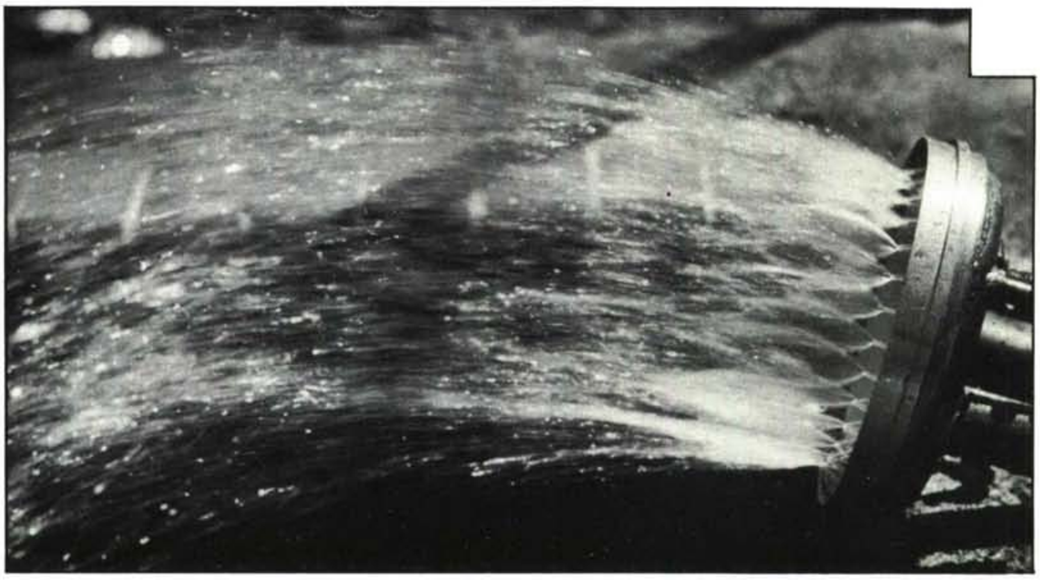
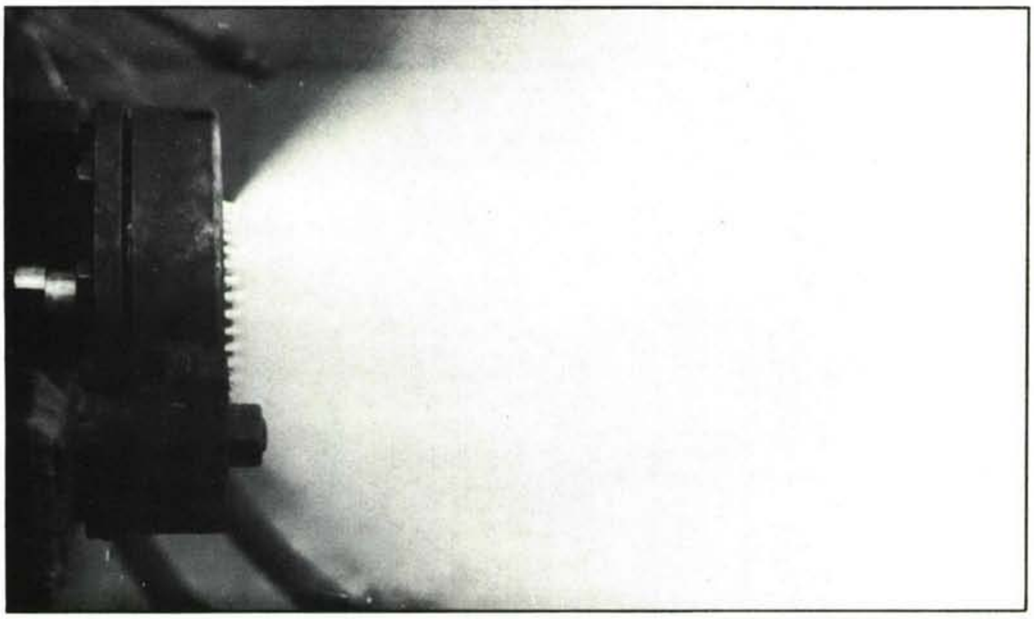


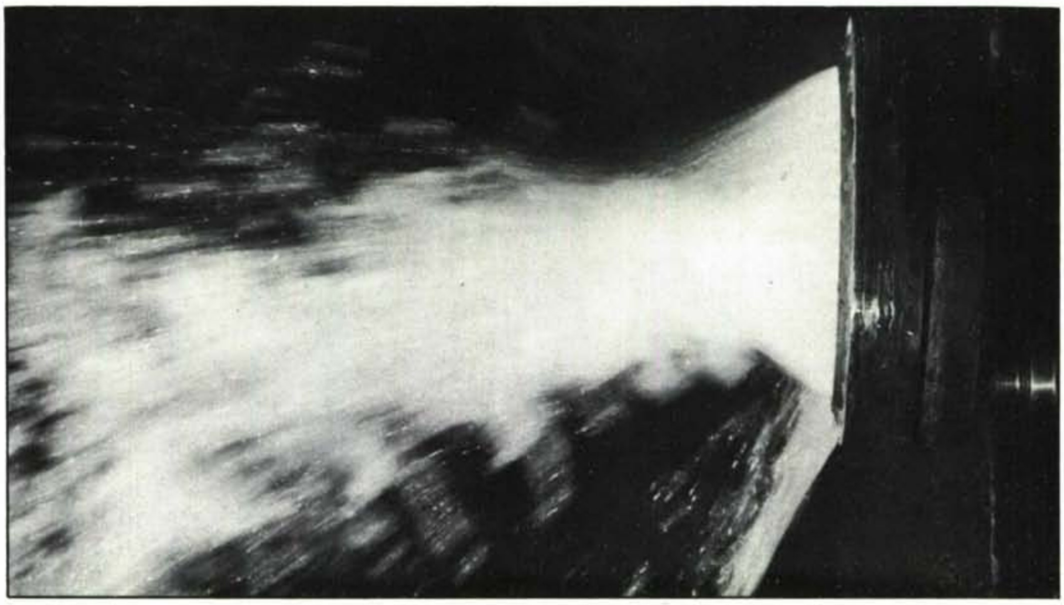
FIG.5. FLANGE TYPE THERMOPILE (WATER)



a. BURNER N.A.7 WITHOUT TARGET PLATE (LOW PRESSURE)



b. BURNER N.A.18, (PRESSURE 140 lb/sq.in.)



c. BURNER N.A.7 WITH TARGET PLATE

FIG.6. WATER FLOW TEST RIG (DIFFERENT BURNERS)

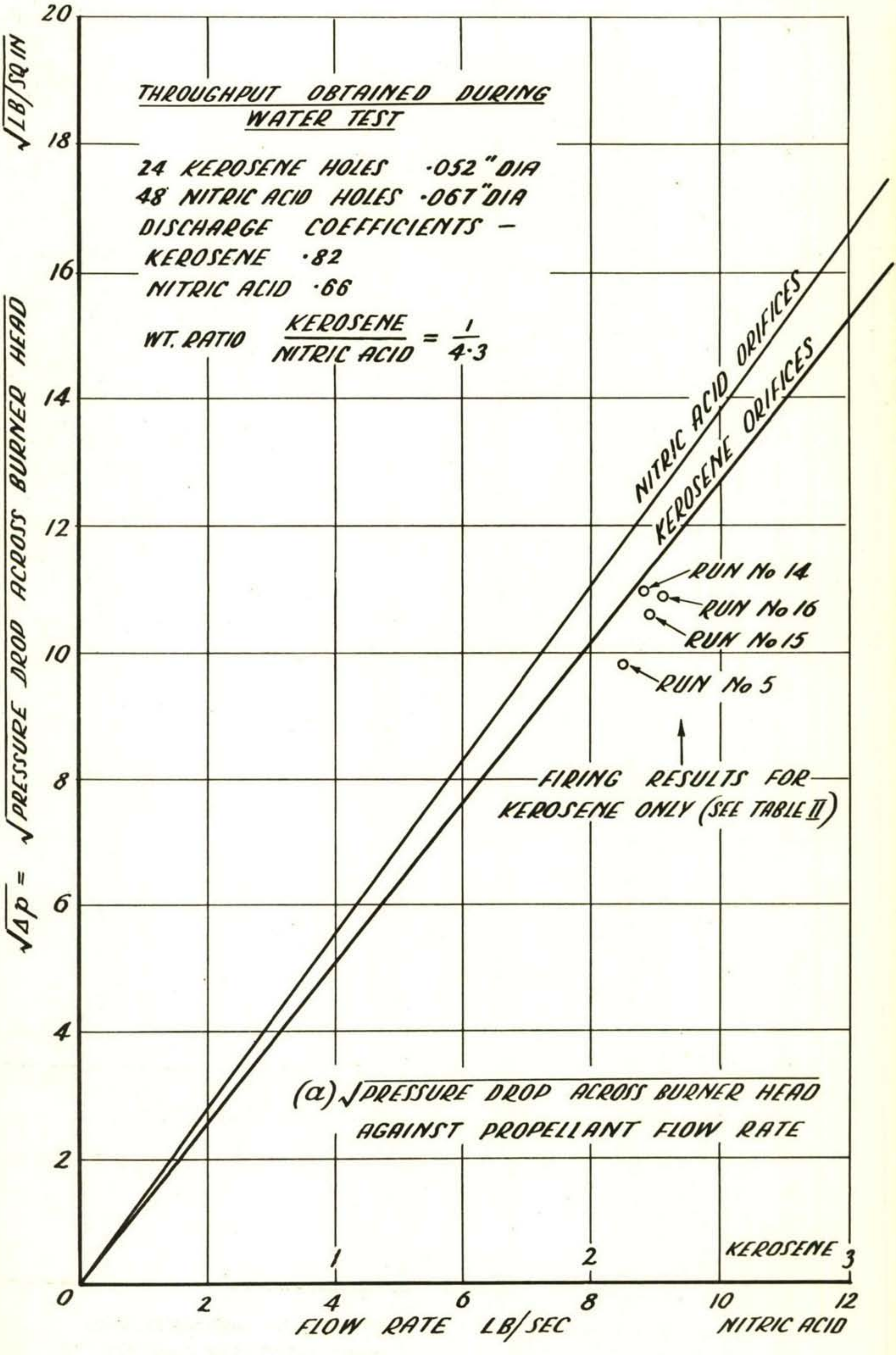


FIG. 7. a. PRESSURE/THROUGHPUT GRAPH FOR BURNER NA-15

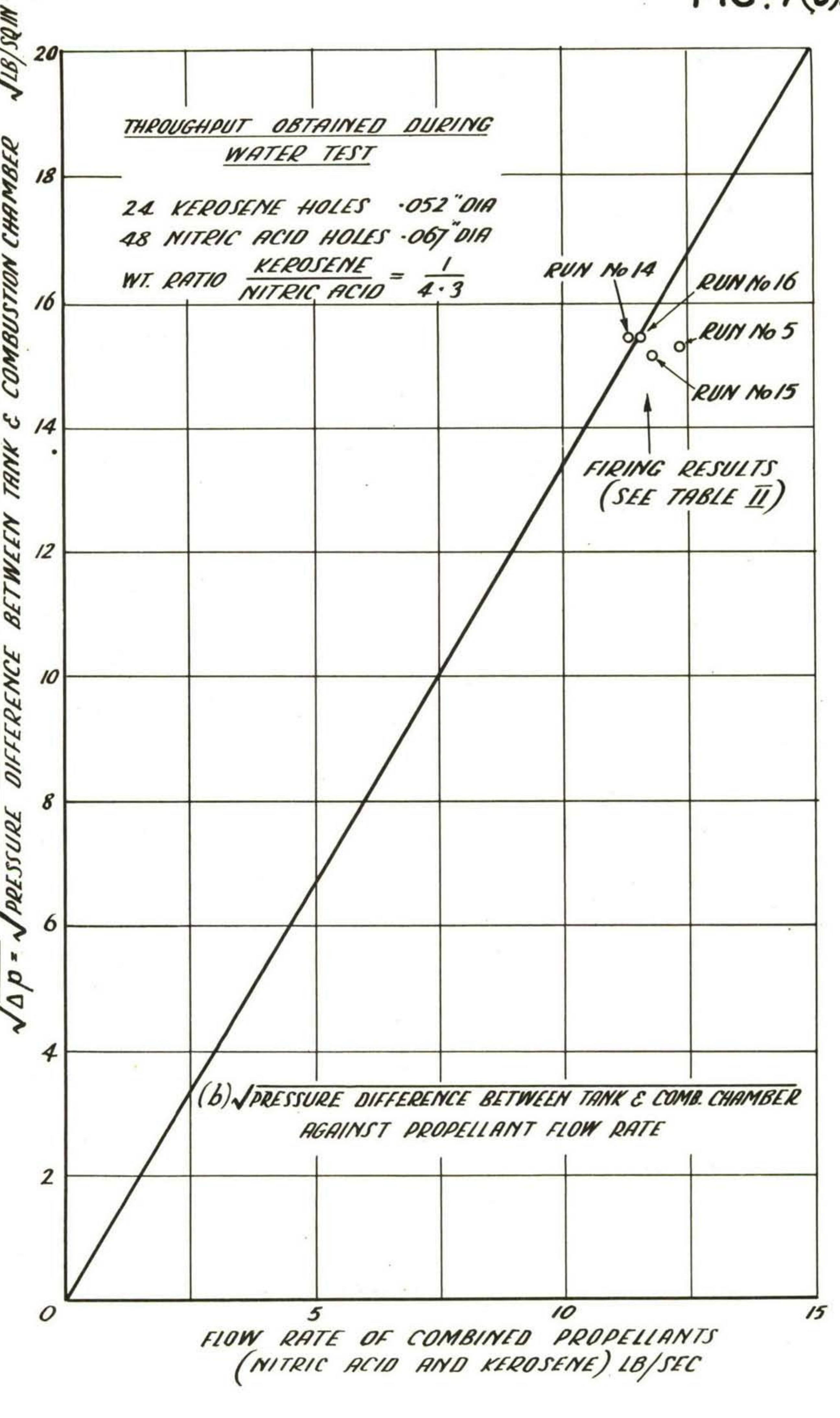


FIG.7 b. PRESSURE / THROUGHPUT GRAPH FOR BURNER N A-15

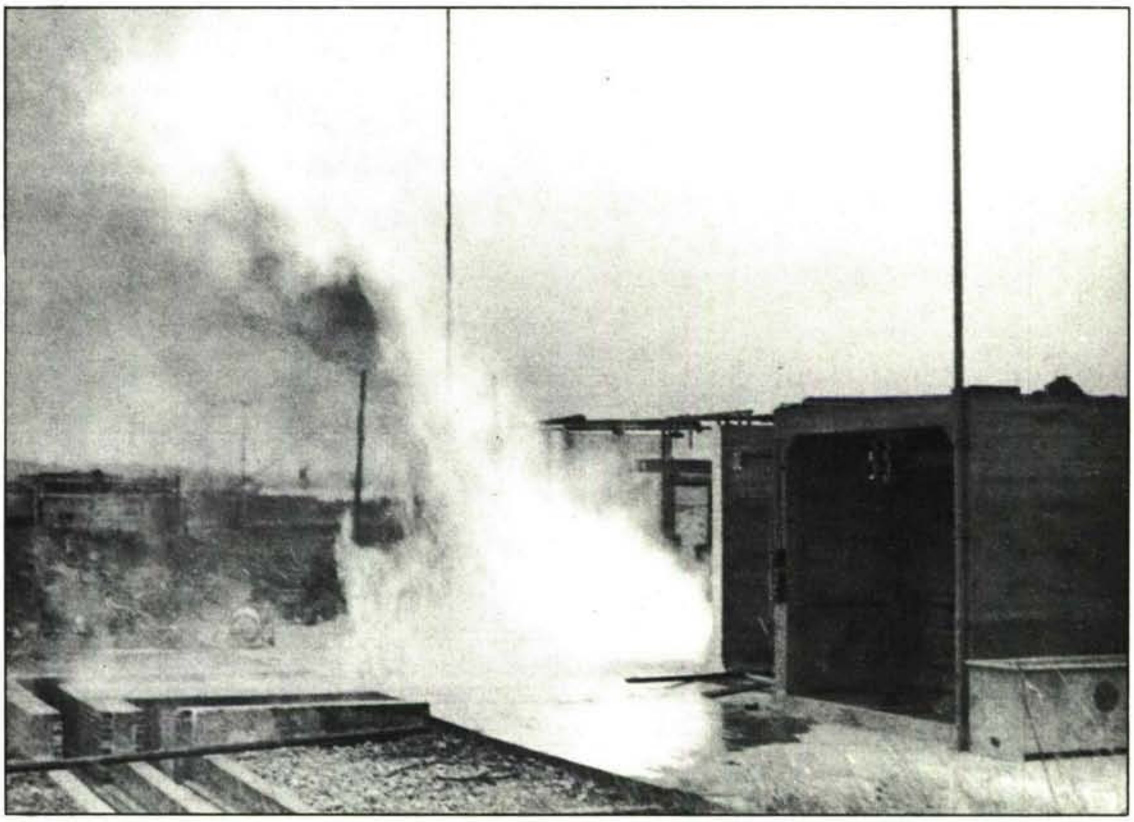
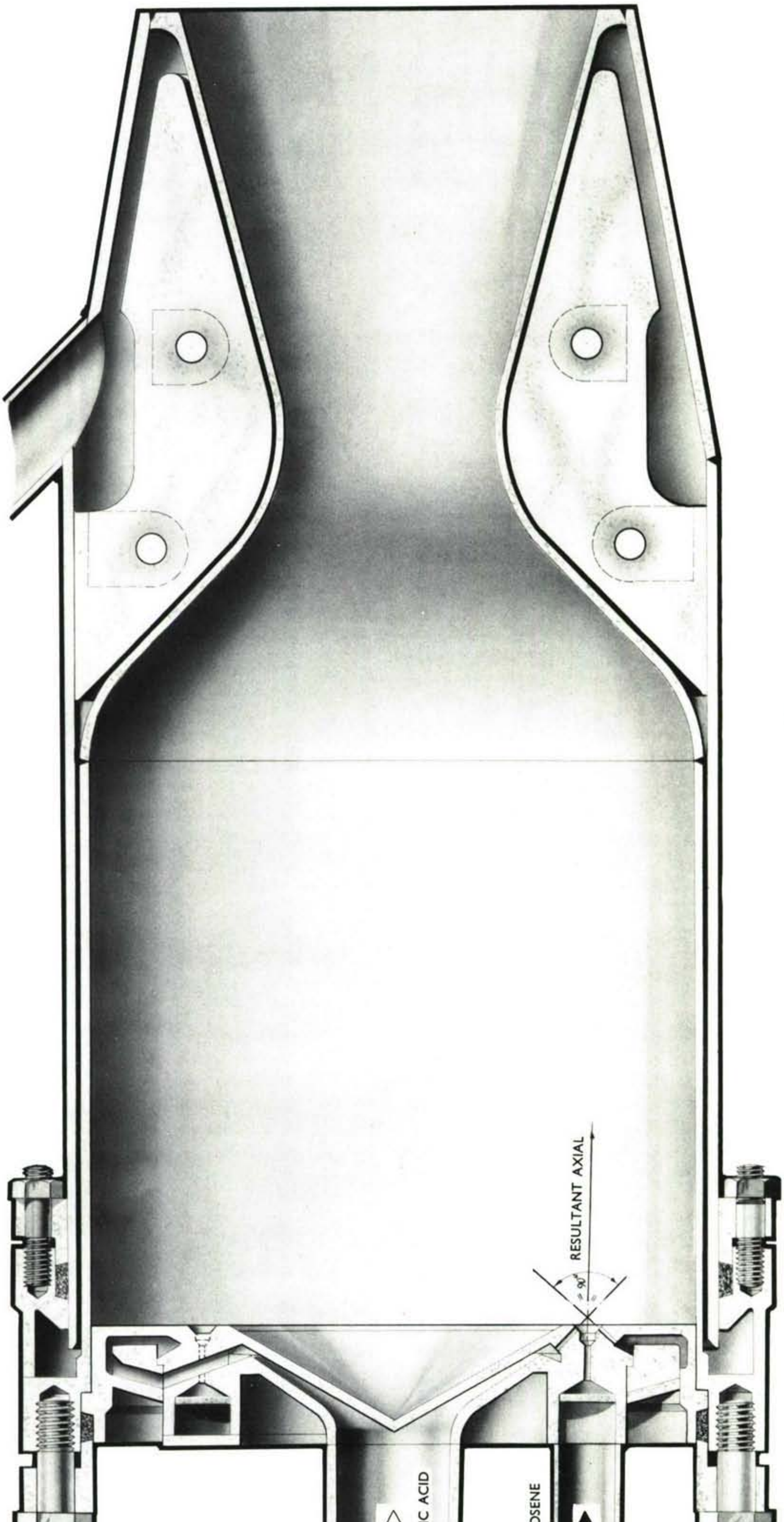


FIG.8. OPEN FIRING

FIG.9



BURNER N.A.15 (STAINLESS STEEL)
INJECTION ORIFICES
NITRIC ACID, 48 HOLES, Dia. 0·067 in., DRILL No.51
KEROSENE, 24 HOLES, Dia. 0·052 in., DRILL No.55

FIG.9. COMBUSTION CHAMBER N.A.107 WITH BURNER N.A.15 (STAINLESS STEEL)

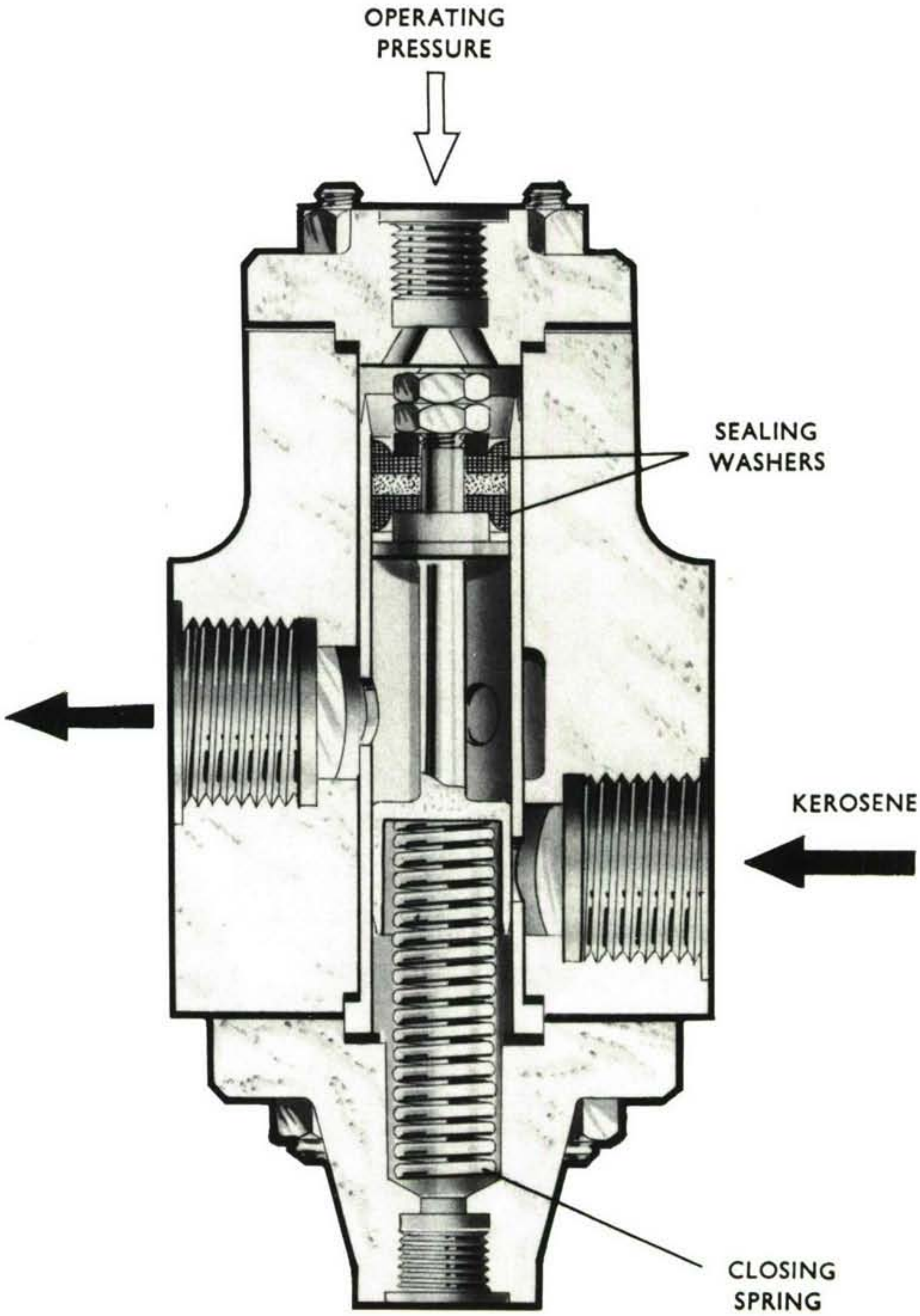


FIG.10. DELAY VALVE

FIG.11

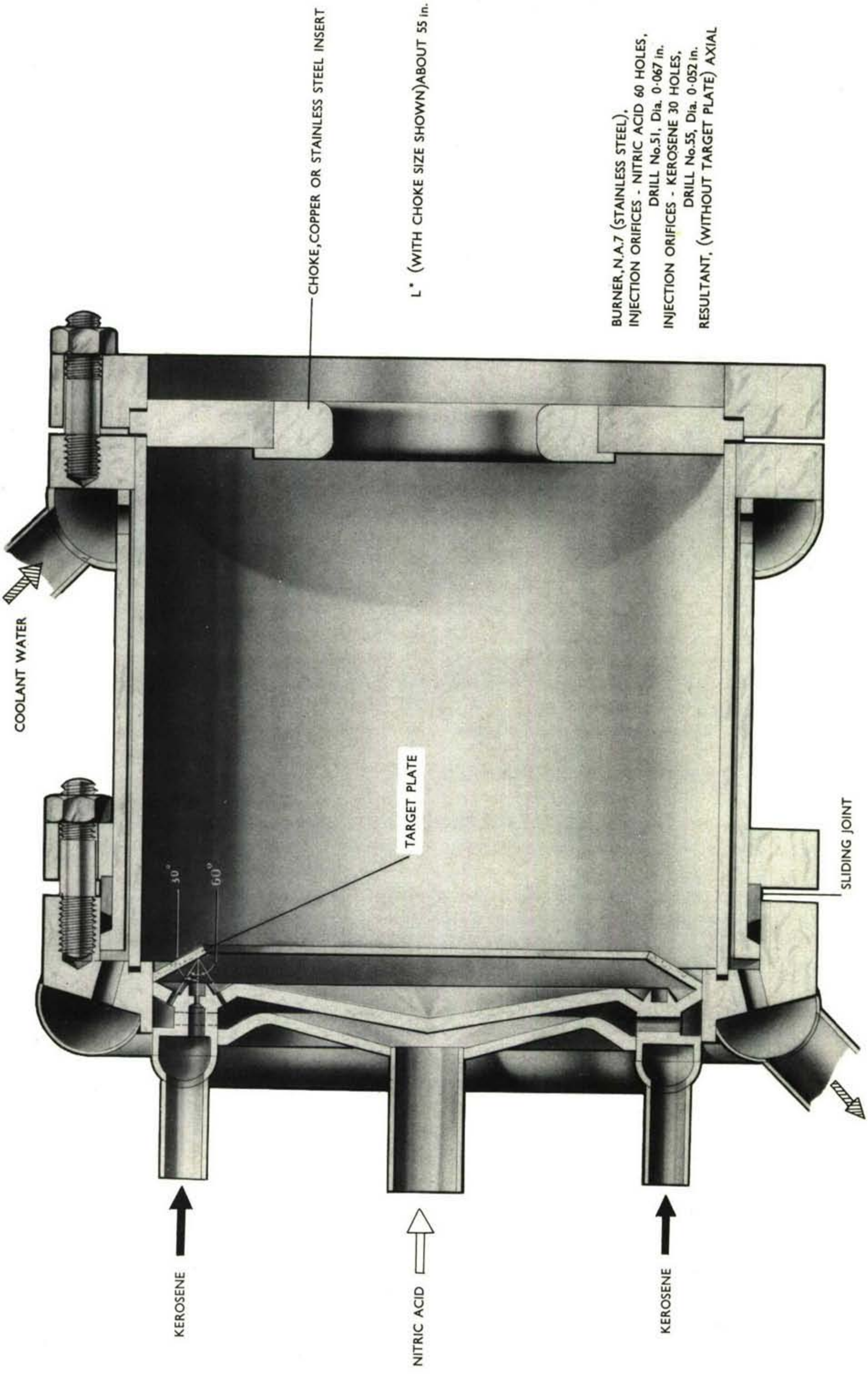


FIG.11. BURNER N.A.7 IN WATER COOLED TUBE CHAMBER (MILD STEEL)

FIG. 12

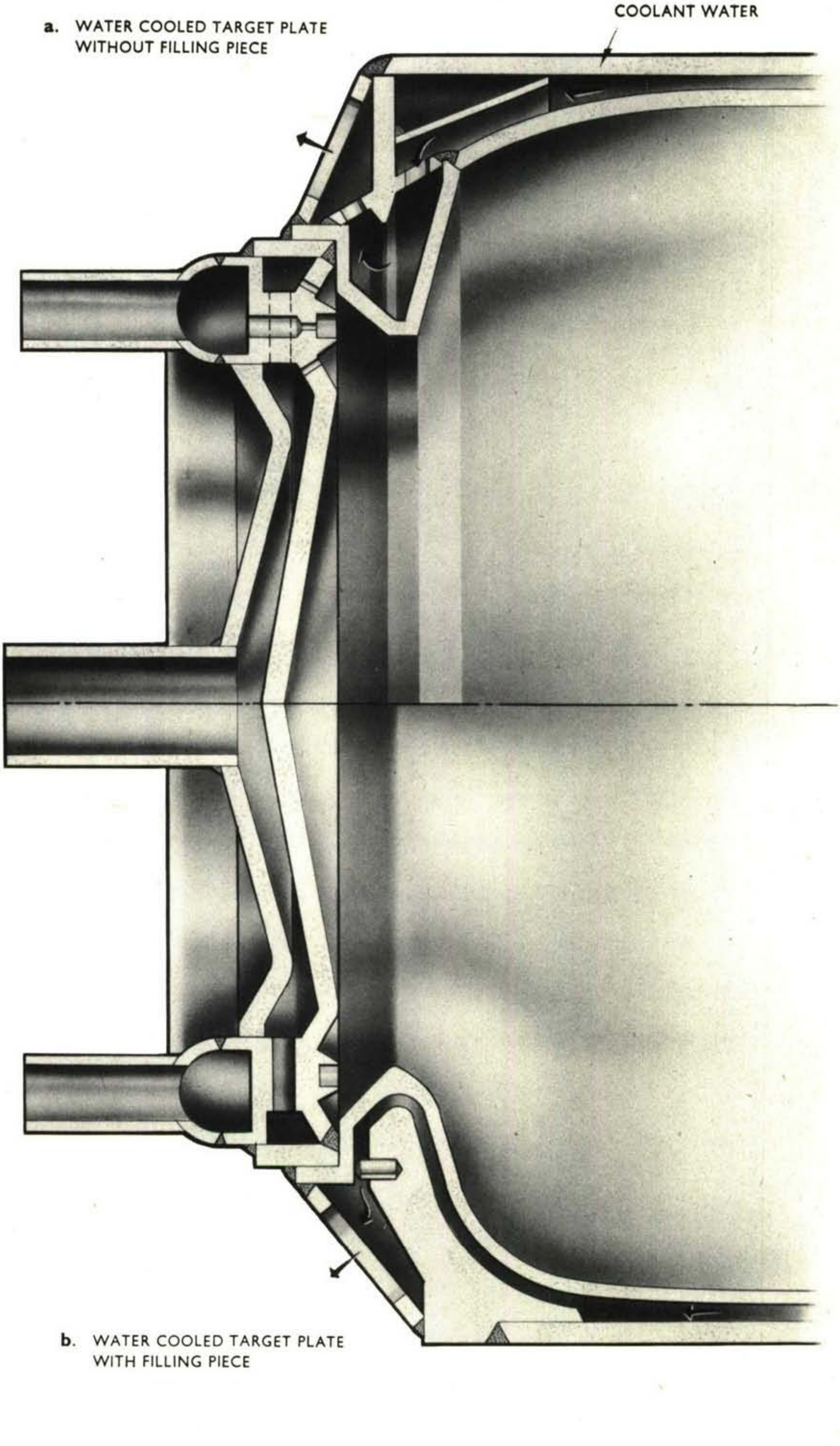


FIG.12. BURNER N.A.7 WITH WATER COOLED CHAMBER AND TARGET PLATE

FIG. 13

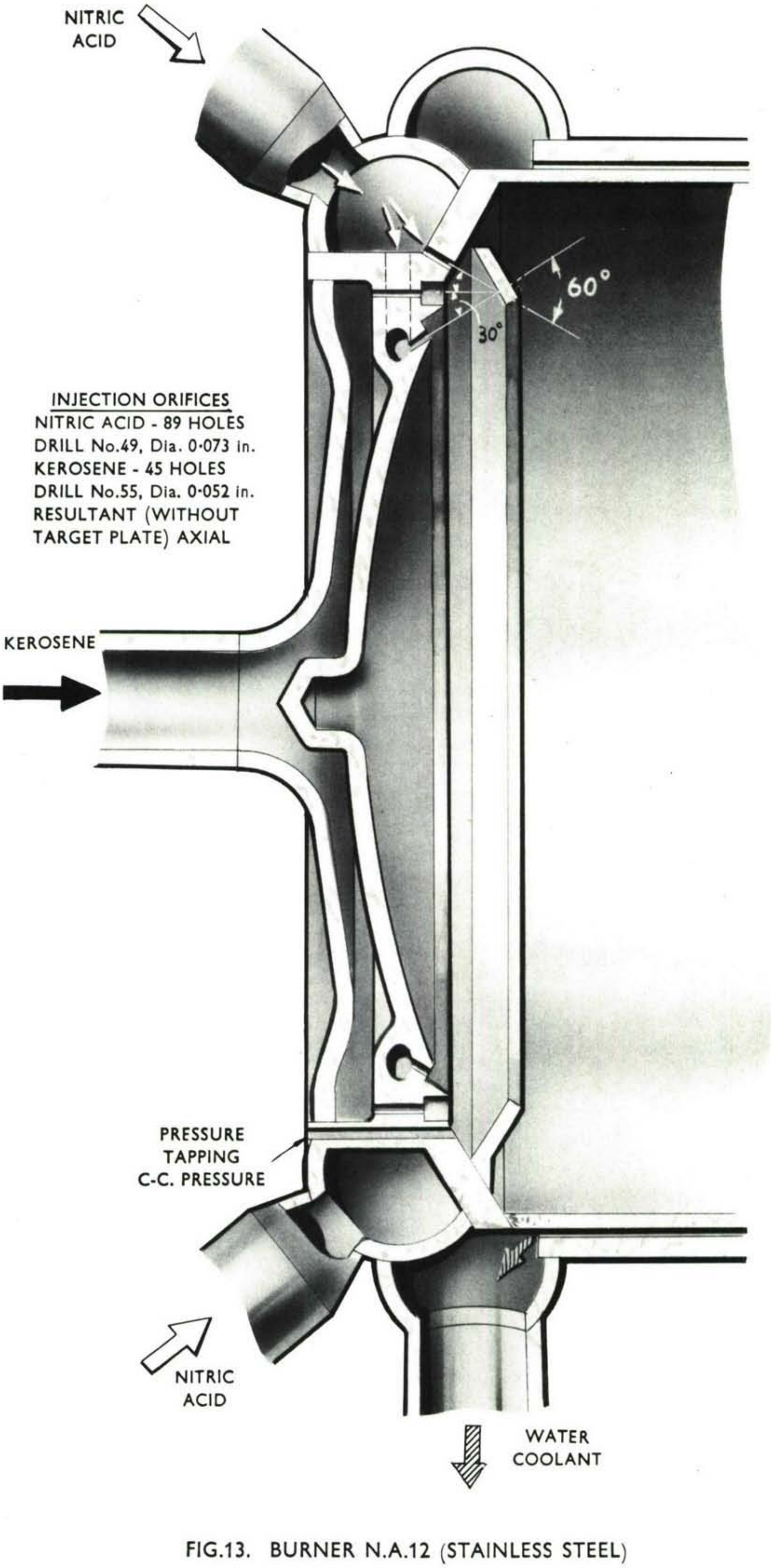
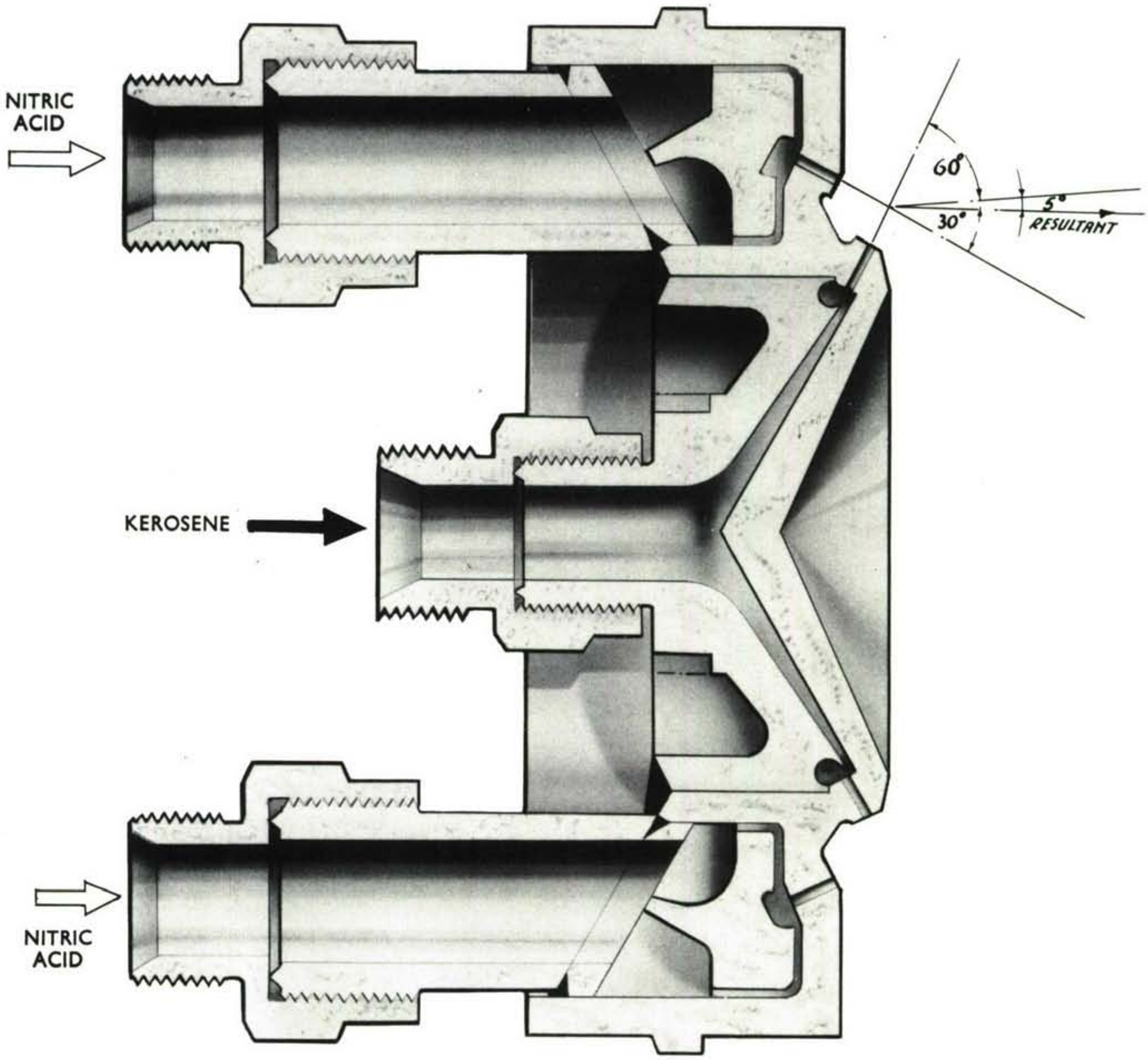
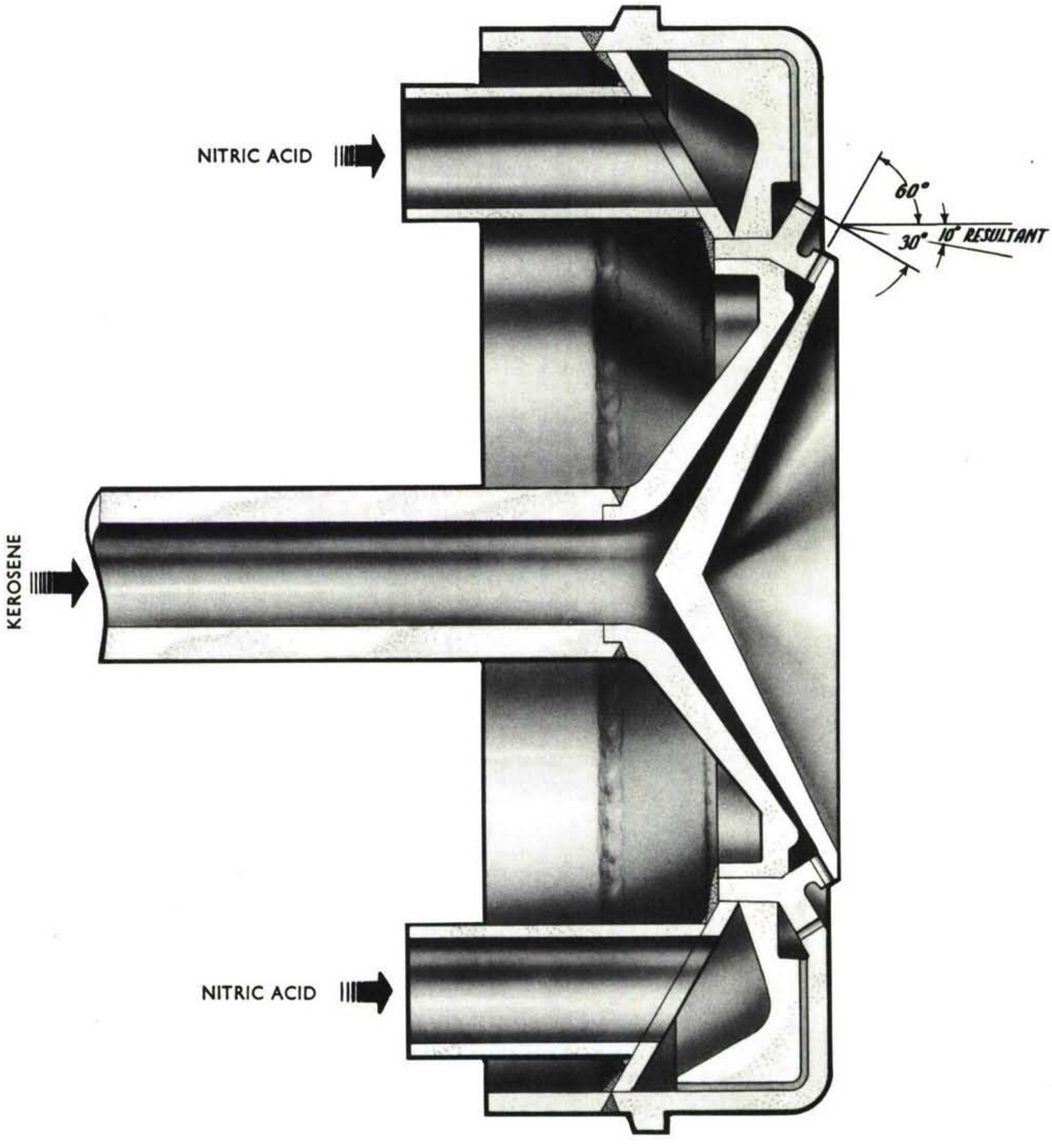


FIG.13. BURNER N.A.12 (STAINLESS STEEL)



INJECTION ORIFICES
N.A.——30 HOLES, DRILL No.42, Dia. 0·0935 in.
KEROSENE-30 HOLES, DRILL No.55, Dia. 0·052 in.

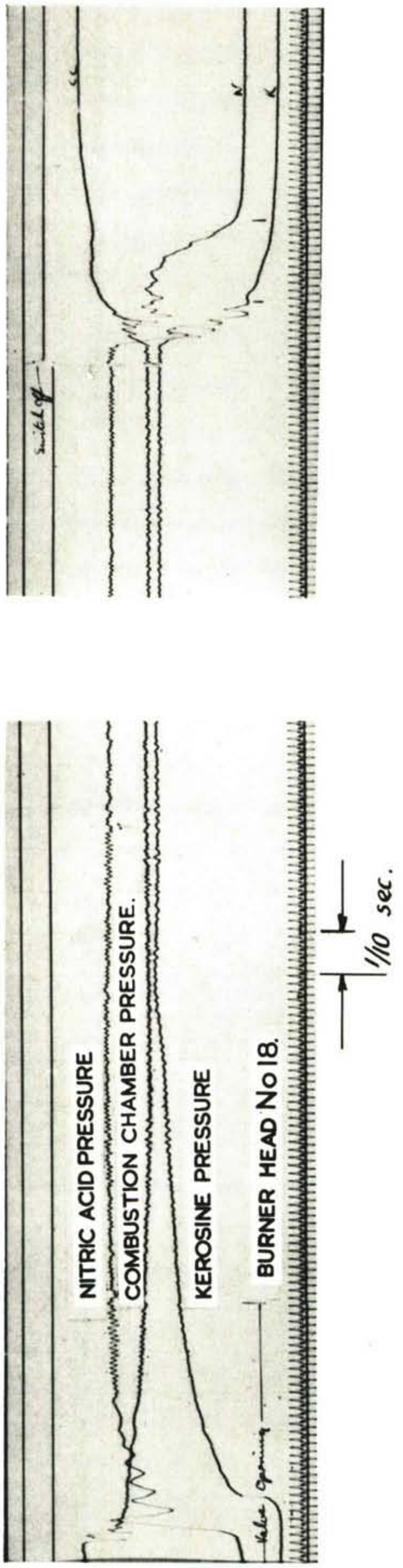
FIG.14. ALUMINIUM BURNER N.A.17



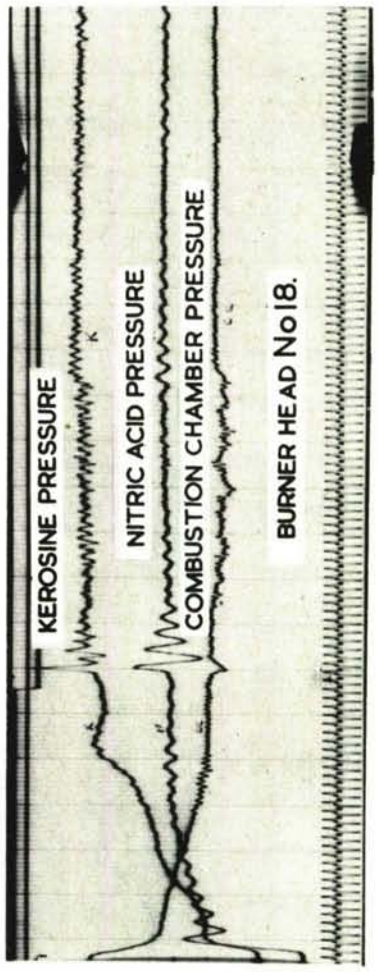
INJECTION ORIFICES
NITRIC ACID-30 HOLES, DRILL No.42, (·0935 in. dia.)
KEROSENE—30 HOLES, DRILL No.55, (·052 in. dia.)

FIG.15. BURNER N.A.18 (STAINLESS STEEL)

FIG.16



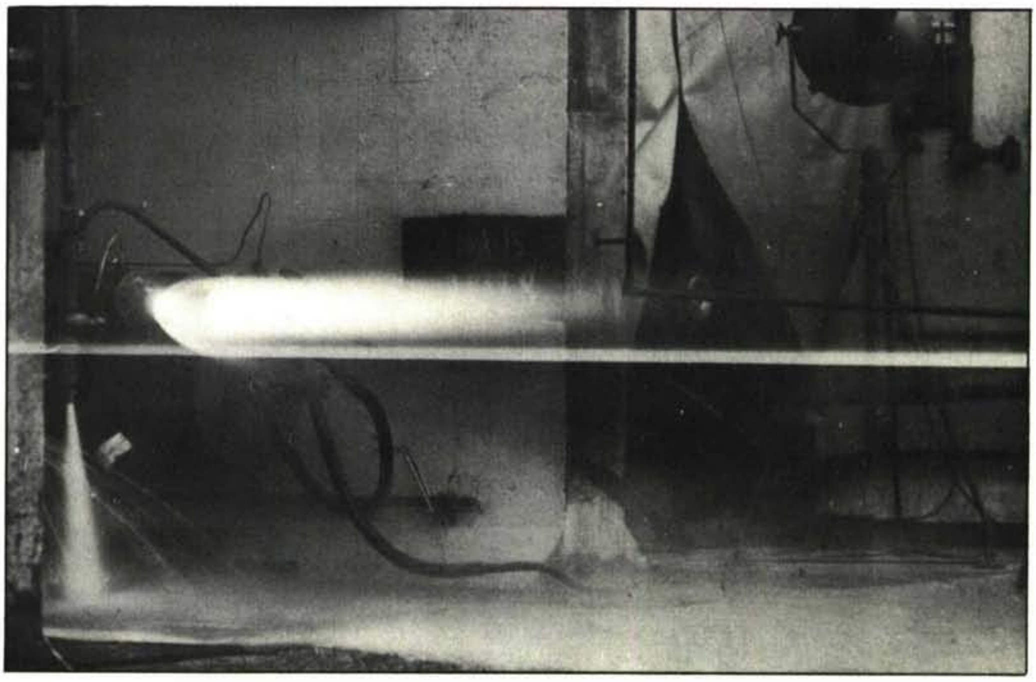
a. "MOCK" CHAMBER



b. WATER COOLED CHAMBER N.A.106

FIG.16. "MILLER" PRESSURE RECORDS, FOR BURNER N.A.18

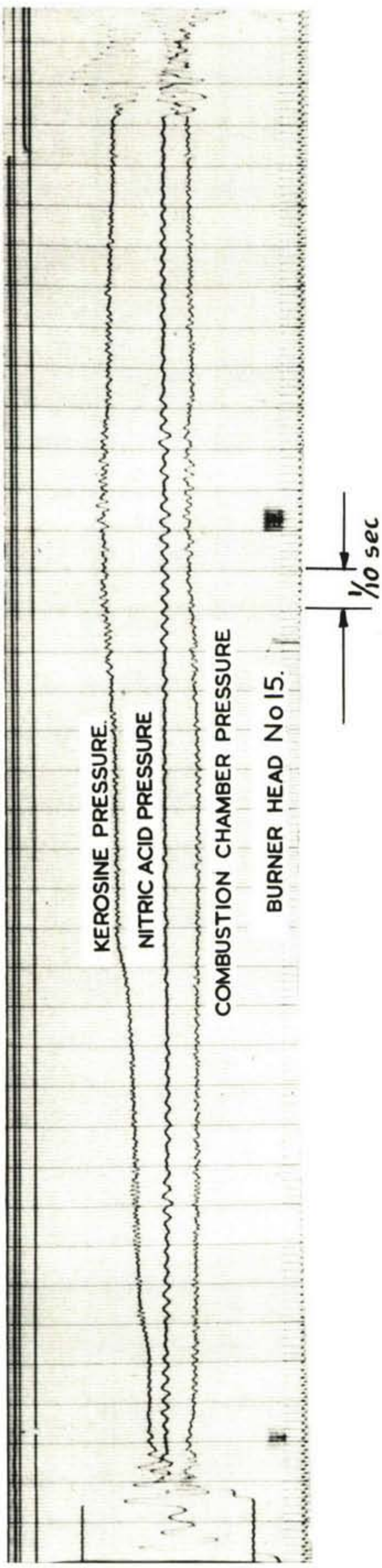
CHAMBER N.A.107



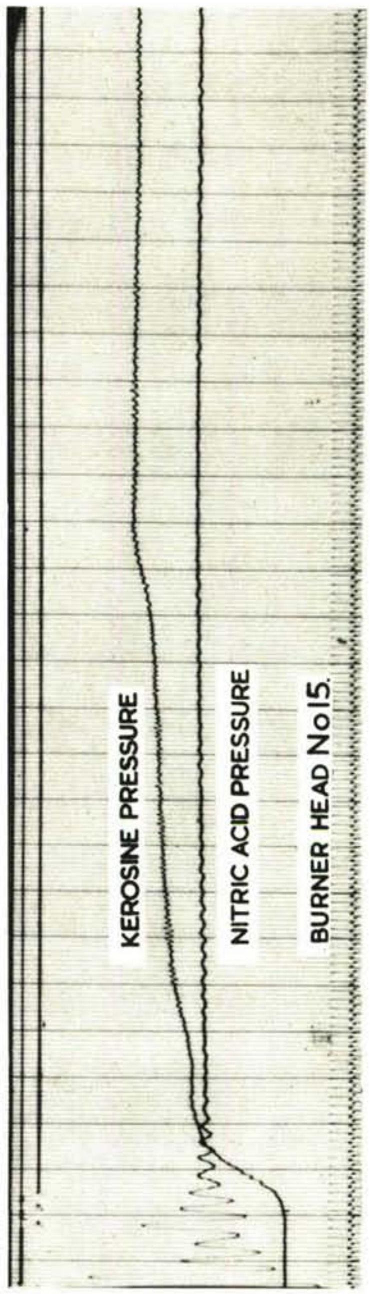
"MOCK" CHAMBER

FIG.17. FIRING WITH BURNER N.A.15

FIG.18



a. MOCK CHAMBER



b. REGENERATIVELY COOLED CHAMBER N.A.107

FIG.18. "MILLER" PRESSURE RECORDS, FOR BURNER N.A.15

UNCLASSIFIED

~~SECRET~~

~~SECRET~~

UNCLASSIFIED